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Low temperature drying process intensification by application
of power ultrasound. Design and development of ultrasonic
drying equipment and systems

Tesis Doctoral

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TABLE OF CONTENTS

TABLE OF CONTENTS.....	viii
LIST OF FIGURES	xiv
LIST OF TABLES.....	xxii
ABSTRACT	1
1.- FUNDAMENTALS OF POWER ULTRASONICS	5
1.1- Introduction	5
1.2- General principles of ultrasound	5
1.3- Power ultrasound industrial applications	9
1.3.1- Brief historical review of the power ultrasound activities of the USTG of the CSIC	10
1.3.1.1- Environmental processes	11
1.3.1.2- Defoaming assisted by power ultrasounds	11
1.3.1.3- Supercritical fluid extraction.	12
1.3.1.4- Drying assisted by power ultrasound.	12
1.4- State of the art in ultrasound-assisted food drying	12
1.4.1- Convective hot-air drying assisted by power ultrasound	12
1.4.1.1- Forced Air Dehydration Assisted by Airborne Ultrasound	12
1.4.1.2- Direct Contact Ultrasonic Dehydration	14
1.4.1.3- Convective hot-air drying using a cylindrical radiating chamber	16
1.4.2- Low temperature drying assisted by ultrasound: APU application with cylindrical radiator (CR)	19
1.4.2.1- Effect of combined ultrasound and LTD/AFD on the kinetics	20
1.4.2.2- Effect of combined ultrasound and LTD/AFD on product quality.....	22
2.- AIRBORNE POWER ULTRASONIC SYSTEMS	23
2.1- Introduction	23
2.2- Description of an airborne power ultrasonic transducer	23
2.2.1- Langevin transducer	24
2.2.2- Mechanical amplifier	27
2.2.3- Extensive radiator	30
2.2.3.1- Circular piston	30
2.2.3.2- Extensive radiators for ultrasonic transducers	32
2.2.4- Macrosonic systems	35
2.3- Nonlinear behavior of a power ultrasonic transducer	36
2.3.1- Dynamic nonlinear effects	37

2.3.2- Nonlinear behavior of Langevin transducers.	38
2.3.3- Vibrational nonlinear effects.	39
2.4- Airborne power ultrasonic transducers for food dehydration purposes.....	41
2.4.1- Power ultrasonic transducer with stepped-grooved circular plate.....	41
2.4.2- Power ultrasonic transducer with flat rectangular plate	43
2.5- Conclusion.	45
3.- NUMERICAL SIMULATION OF ULTRASONIC SYSTEMS	47
3.1- Introduction	47
3.2- Fundamentals of the numerical design of an airborne power ultrasonic transducer.	48
3.2.1- General principles of numerical simulation using COMSOL Multiphysics®	48
3.2.2- Specific process for the simulation of a power ultrasonic transducer using FEM	49
3.3- Numerical design of an airborne power ultrasonic transducer with stepped-grooved circular plate.	53
3.3.1- Numerical design of the vibrator tuned at 26 kHz	53
3.3.1.1- Eigenfrequency analysis of a vibrator tuned at 26 kHz.....	53
3.3.1.2- Frequency domain analysis of the vibrator tuned at 26 kHz	56
3.3.2- Numerical design of the stepped-grooved circular radiator.....	58
3.3.3- Analysis of the behavior of the whole system	61
3.4- Numerical design of an airborne power ultrasonic transducer with flat rectangular plate. .	65
3.4.1- Numerical design of the vibrator operating at 22 kHz.....	65
3.4.1.1- Eigenfrequency analysis.....	67
3.4.1.2- Frequency domain analysis	68
3.4.2- Design of the flat rectangular radiator.....	70
3.4.2.1- Theoretical approach to the vibration of rectangular plates.....	70
3.4.2.2- Numerical analysis of the flat rectangular plates	74
3.4.3- Analysis of the behavior of the whole system	75
3.5- Numerical simulation of the ultrasonic field.....	78
3.5.1- Meshing definition for the numerical analysis of the acoustic field.....	79
3.5.2- Acoustic field generated by an airborne power ultrasonic transducer with stepped-grooved circular plate.....	80
3.5.3- Acoustic field generated by an airborne power ultrasonic transducer with flat rectangular plate.....	83
3.5.3.1- Acoustic field generated by an APUT with flat rectangular plate without reflectors.....	83
3.5.3.2- Acoustic field generated by an APUT with flat rectangular plate with reflectors	88
3.6- Conclusion.	92

4.- EXPERIMENTAL CHARACTERIZATION OF AIRBORNE POWER ULTRASONIC TRANSDUCERS	95
4.1- Low power characterization.	96
4.2- Stability tests.	97
4.3- Nonlinear dynamics characterization.	101
4.3.2- Determination of the nonlinear behavior of an airborne power ultrasonic transducer	102
4.3.2.1- Nonlinear experiments under continuous operation regime	102
4.3.2.2- Frequency sweeps.....	103
4.3.2.3- Spectral distribution of the energy.....	105
4.4- Experimental modal analysis.	105
4.5- Acoustic characterization.	108
4.5.1- System for the experimental determination of the ultrasonic field.....	109
4.5.2- Experimental determination of the directivity pattern of an ultrasonic system.....	111
4.6- Conclusion.	112
5.- DEVELOPMENT OF POWER ULTRASONIC SYSTEMS	113
5.1- Development of an airborne power ultrasonic transducer with stepped-grooved circular radiator.	113
5.1.1- Low power characterization of the APUT with circular radiator in the impedance analyzer.	113
5.1.2- Stability tests done over the APUT with circular radiator.....	113
5.1.3- Nonlinear dynamic characterization of the APUT with stepped-grooved circular radiator.	115
5.1.3.1- Nonlinear characterization under continuous operation regime	115
5.1.3.2- Nonlinear characterization with frequency sweeps around resonance.....	118
5.1.3.3- FFT experiments with the APU transducer operating at high power regime.....	121
5.1.4- Experimental modal analysis of the APUT with stepped-grooved circular radiator. ...	122
5.1.5- Acoustic characterization of the APUT with stepped-grooved circular radiator.	124
5.2- Development of an airborne power ultrasonic transducer with flat rectangular radiator and a reflectors system.....	128
5.2.1- Low power characterization of the APUT with flat rectangular radiator in the impedance analyzer.	128
5.2.2- Stability tests done over the APUT with flat rectangular radiator.	129
5.2.3- Nonlinear dynamic characterization of the APUT with flat rectangular radiator.	130
5.2.3.1- Nonlinear characterization under continuous operation regime	131
5.2.3.2- Nonlinear characterization with frequency sweeps around resonance.....	133
5.2.3.3- FFT experiments with the transducer operating at high power regime.....	136
5.2.4- Experimental modal analysis of the APUT with flat rectangular radiator.....	138

5.2.5- Acoustic characterization of the APUT with flat rectangular radiator	140
5.2.5.1- Ultrasonic field generated by the APUT with flat rectangular radiator without and with a reflector system	140
5.2.5.2- Directivity pattern of the ultrasonic field generated by the APUT with flat rectangular radiator without and with a reflector system.....	145
5.3- Design of an adaptive mechanical amplifier for rectangular radiators.....	146
5.3.1- Design of the airborne power ultrasonic transducer	147
5.3.2- Numerical analysis of the configurations of the mechanical amplifier	149
5.3.3- Experimental analysis of the performance of a rectangular plate transducer with different configurations of the mechanical amplifier	150
5.3.3.1- Response of the transducer in the impedance analyzer	150
5.3.3.2- Stability analysis of the transducer with different adapters	151
5.3.3.3- Dynamic analysis of the transducer with different adapters	154
5.3.4- Summary of the results obtained with the five configurations analyzed.....	159
5.4- Conclusion.	160
6.- AIRBORNE POWER ULTRASOUND FOR DRYING PROCESSES INTENSIFICATION AT LOW TEMPERATURE: USE OF A STEPPED-GROOVED PLATE TRANSDUCER	163
6.1- Introduction.	163
6.2- Materials and methods.....	165
6.2.1- AFD drier with APU application by stepped circular plate radiator (SCPR)	165
6.2.2- Acoustic properties of the dehydration chamber	168
6.2.2.1- Numerical characterization of the acoustic properties of the dehydration chamber	168
6.2.2.2- Experimental characterization of the acoustic properties of the dehydration chamber	171
6.2.3- Drying kinetics. Numerical model	176
6.3- Experimental campaign.	177
6.3.1- Raw material and moisture content	177
6.3.2- Atmospheric freeze-drying experiments.....	178
6.4- Results and discussion.	182
6.4.1- Influence of the applied electric power in the drying kinetics.....	182
6.4.1.1- Experiments at about -12 °C	182
6.4.1.2- Experiments at about -8 °C	185
6.4.2- Influence of the dehydration temperature in drying kinetics	187
6.4.2.1- Experiments without ultrasounds.....	187
6.4.2.2- Experiments with power ultrasounds (200 W).....	189
6.5- Conclusions.	190
7.- CONCLUSIONS	193

7.1- Ultrasonic systems for lyophilization at atmospheric pressure	193
7.1.1- APU transducer with stepped-grooved circular radiator	194
7.1.2- APU transducer with flat rectangular radiator and a reflectors system.....	195
7.2- Effect of the shape of the horn in APUT's with rectangular radiator	196
7.3- Effect of the application of power ultrasounds in food dehydration	197
7.4- Final conclusion and future work	198
ANNEX A.- EFFECTS OF NONLINEAR PHENOMENA CREATED BY POWER ULTRASOUND	201
ANNEX B.- ELECTROMECHANICAL ANALOGIES.....	207
B.1- Piezoelectricity: Fundamentals.	207
B.2- Electrical and mechanical analogies of an APUT.	213
B.2.1- Equivalent circuit of a piezoelectric transducer.....	214
B.3- Electronic excitation equipment.	215
ANNEX C.- SIMULATION OF THE MECHANICAL PRESTRESS IN POWER ULTRASONIC TRANSDUCERS	217
C.1- Simulation of the mechanical prestress in 3D models.....	217
C.1.1- Eigenfrequency analysis.....	218
C.1.2- Frequency domain study.	220
C.2- Simulation of the mechanical prestress in 2D axisymmetric models.....	221
ANNEX D.- ADDITIONAL RESULTS OBTAINED IN THE NUMERICAL SIMULATIONS OF AIRBORNE POWER ULTRASONIC TRANSDUCERS	225
D.1- Mode shapes corresponding to the different eigenmodes of the vibrator tuned around 26 kHz.....	225
D.2- Mode shapes corresponding to the different eigenmodes of the stepped-grooved circular radiator.	226
D.3- Mode shapes corresponding to the different eigenmodes of the APU transducer with stepped-grooved circular radiator.	227
D.4- Mode shapes corresponding to the different eigenmodes of the vibrator tuned around 21 kHz.	228
D.5- Mode shapes corresponding to the different eigenmodes of the flat rectangular radiator.	228
D.6- Mode shapes corresponding to the different eigenmodes of the APU transducer with flat rectangular radiator.....	229
ANNEX E.- PHYSICAL PROPERTIES OF THE MATERIALS	231
ANNEX F.- DESIGN OF AN ADAPTATIVE MECHANICAL AMPLIFIER FOR RECTANGULAR RADIATORS. TABLES AND FIGURES	233
F.1- Vibration modes near the operational one with two nodal lines.	233
F.2- Numerical simulation of the airborne power ultrasonic transducer with the five adapters.	233
F.2.1- Adapter with circular shape.....	233

F.2.2- Adapter with long-rounded shape	235
F.2.3- Adapter with squared shape	238
F.2.4- Adapter with rectangular shape	240
ANNEX G.- DESCRIPTION OF THE TWO DYNAMIC CHARACTERIZATION SYSTEMS	245
G.1- Old system for the nonlinear dynamics characterization of APU transducers	245
G.2- New system for the nonlinear dynamics characterization of APU transducers	245
G.3- Comparison between the two systems for the nonlinear dynamics characterization of the APUT	251
ANNEX H.- PUBLICATIONS	253
H.1- Journal papers.	253
H.2- Book chapters.	253
H.3- Conference papers.	253
H.4- Contributions in international conferences and symposiums.	254
H.5- Contributions in national conferences and symposiums.	255
BIBLIOGRAPHY	257

LIST OF FIGURES

1.- FUNDAMENTALS OF POWER ULTRASONICS

Fig.1.1.- Experimental set-up for forced hot air drying assisted by APU	13
Fig.1.2.- Forced hot-air dehydration kinetics of carrot at 1.3 m/s without and with APU (155 dB)..	14
Fig.1.3.- Forced hot-air dehydration kinetics of carrot at 1.6 m/s without and with APU (163 dB)..	14
Fig.1.4.- Experimental set-up for dehydration by direct contact ultrasonic vibration	15
Fig.1.5.- Dehydration kinetics of carrot slices by direct contact ultrasonic vibration (100W) and various flow velocities.	15
Fig.1.6.- Scheme of the direct contact multi-sample ultrasonic dehydration system.....	16
Fig.1.7.- Ultrasonic assisted dryer.	17
Fig.1.8.- Drying kinetics of eggplant at 40°C and 1 m/s with different ultrasonic power.....	18
Fig.1.9.- Influence of the ultrasonic power on k and D_e for drying of potato at 40 °C and 1 m/s.	19
Fig.1.10.- Influence of the hardness of the material being dried on the ultrasonic effectiveness. ...	19
Fig.1.11.- Representation of the AFD chamber with cylindrical radiator[62].....	20

2.- AIRBORNE POWER ULTRASONIC SYSTEMS

Fig.2.1.- Basic structure of an airborne power ultrasonic transducer.....	24
Fig.2.2.- Scheme of the basic structure of a Langevin type transducer (or sandwich).....	24
Fig.2.3.- Components of a Langevin type transducer.....	25
Fig.2.4.- Thickness mode of a Langevin transducer.....	26
Fig.2.5.- Fatigue strength T_f , prestress T_0 and maximum permissible stress amplitude T_{cmax} in the center of the transducer.....	27
Fig.2.6.- Distribution of velocity and stress in four types of mechanical amplifiers.....	28
Fig.2.7.- Double cylindrical mechanical amplifier.	29
Fig.2.8.- Effect of the mechanical amplifier in the value of the vibration amplitude.	29
Fig.2.9.- Axial acoustic intensity of an ideal circular piston radiating in air.	30
Fig.2.10.- 2D acoustic field generated by an ideal circular piston.	31
Fig.2.11.- Directivity pattern of a circular piston.	31
Fig.2.12.- Transducer driven by means of a piezoelectric element.....	32
Fig.2.13.- Operational mode with 7 NC of a flat circular plate.....	33
Fig.2.14.- Acoustic field generated by a flat circular radiator vibrating in a 7NC mode.....	33
Fig.2.15.- Modified plate for coherent radiation.	34
Fig.2.16.- Scheme for the design of focusing radiators.....	35
Fig.2.17.- Acoustic field of a focusing circular plate transducer.....	35
Fig.2.18.- Structure of the first ultrasonic system for high power applications in gases.	36
Fig.2.19.- Frequency response curves of the Duffing equation depending on the value of γ	38
Fig.2.20.- Jump phenomenon and hysteresis in a system with a softening behavior.	38
Fig.2.21.- Distorted signal in time and frequency domains.....	38

Fig.2.22.- Nonlinear dynamic behavior of a Langevin transducer.	39
Fig.2.23.- Vibration velocity of an APU transducer exposed to a low power excitation.	40
Fig.2.24.- Normalized vibration velocity frequency responses obtained via upward and downward sweeps around the working frequency.	41
Fig.2.25.- Vibration velocity spectrum measured on the plate for a 300V excitation.	41
Fig.2.26.- Airborne power ultrasonic transducer with stepped-grooved circular radiator for food dehydration processes.	42
Fig.2.27.- Half wavelength deep steps applied in a circular plate for coherent radiation.	42
Fig.2.28.- APU transducer with flat rectangular radiator and a reflectors system.	43
Fig.2.29.- Food dehydration system with an APU transducer and a reflectors system.	44
Fig.2.30.- APU transducer with a rectangular plate radiator.	45

3.- NUMERICAL SIMULATION OF ULTRASONIC SYSTEMS

Fig. 3.1.- Piezoelectric ceramics for airborne power ultrasonic transducers.	50
Fig. 3.2.- Section of an ultrasonic vibrator.	51
Fig. 3.3.- Boundary conditions of the electrostatics interface.	52
Fig. 3.4.- Mesh of the vibrator tuned at 26 kHz.	54
Fig. 3.5.- 2D axisymmetric and 3D views of the working mode of the vibrator at 28492 Hz.	55
Fig. 3.6.- Spectral response of the vibrator in terms of displacement.	55
Fig. 3.7.- Spectral response of the vibrator in terms of conductance.	56
Fig. 3.8.- Displacement at the tip of the horn around the resonance frequency.	57
Fig. 3.9.- Displacement along the vibrator.	57
Fig. 3.10.- Profile of the stepped-grooved circular radiator.	58
Fig. 3.11.- 3D model of the stepped-grooved circular radiator.	59
Fig. 3.12.- Mesh of the 3D stepped-grooved circular radiator.	60
Fig. 3.13.- Operational mode of the stepped-grooved circular radiator at 25808 Hz.	60
Fig. 3.14.- 2D axisymmetric geometry of the APUT with stepped-grooved circular plate.	61
Fig. 3.15.- Mesh of the APU transducer with stepped-grooved circular radiator.	62
Fig. 3.16.- Operational mode of the APU transducer with stepped-grooved circular radiator.	62
Fig. 3.17.- Displacement at the bolt of the plate around the resonance frequency.	63
Fig. 3.18.- Distribution of displacements along the radius of the circular plate.	64
Fig. 3.19.- Evolution of the mechanical stress suffered by each component.	65
Fig. 3.20.- 3D model of the vibrator tuned at 21 kHz.	66
Fig. 3.21.- Mesh of the vibrator tuned at 22 kHz.	67
Fig. 3.22.- Extensional mode of the vibrator at 22774 Hz.	67
Fig. 3.23.- Spectral response of the vibrator in terms of displacement.	68
Fig. 3.24.- Spectral response of the vibrator in terms of conductance.	68
Fig. 3.25.- Displacement at the tip of the horn around the resonance frequency.	69
Fig. 3.26.- Displacement along the vibrator.	69
Fig. 3.27.- Model of the flat rectangular radiator.	70

Fig. 3.28.- Operational mode with 12 NL of the rectangular plate.	72
Fig. 3.29.- Accuracy of the theoretical study of vibration of a rectangular plate.	72
Fig. 3.30.- Accuracy of the corrected equation of the vibration of a rectangular plate.	73
Fig. 3.31.- Mesh of the flat rectangular radiator.	74
Fig. 3.32.- 3D geometry of the APU transducer with flat rectangular plate.	75
Fig. 3.33.- Mesh of the APU transducer flat rectangular radiator.	75
Fig. 3.34.- Operational mode of the APU transducer with flat rectangular radiator.	76
Fig. 3.35.- Displacement obtained in the plate around the resonance frequency.	76
Fig. 3.36.- Distribution of displacements along the rectangular plate.	77
Fig. 3.37.- Evolution of the mechanical stress suffered by each component.	78
Fig. 3.38.- Location and magnitude of the prescribed displacement applied to the bolt.	81
Fig. 3.39.- Mesh of the geometry for the simulation of the acoustic field.	82
Fig. 3.40.- Axial acoustic pressure generated by the stepped circular radiator.	82
Fig. 3.41.- Pressure distribution generated by the APUT with stepped-grooved circular radiator. .	83
Fig. 3.42.- Geometry for the simulation of the acoustic field generated by a flat rectangular APUT. .	85
Fig. 3.43.- Axial acoustic pressure generated by the flat rectangular radiator.	85
Fig. 3.44.- Geometry and mesh for 3 m chamber.	86
Fig. 3.45.- 2D numerical simulation of the acoustic field in the XY plane generated by a flat rectangular APUT vibrating at its operational mode.	86
Fig. 3.46.- Geometry and mesh for 3D model.	87
Fig. 3.47.- Slices in the YZ plane, parallel to the flat radiator, at different distances.	87
Fig. 3.48.- Acoustic pressure distribution in the plane XZ up to 1.1 m.	88
Fig. 3.49.- Model of the ultrasonic system with reflectors (SWR).	88
Fig. 3.50.- Quarter of the model of the ultrasonic SWR.	89
Fig. 3.51.- Mesh of the ultrasonic SWR.	89
Fig. 3.52.- Acoustic distribution inside the reflectors system.	90
Fig. 3.53.- Geometry and mesh for the simulation of the acoustic field.	91
Fig. 3.54.- Pressure distribution under free field conditions, generated by the ultrasonic SWR.	91
Fig. 3.55.- Slices in the YZ plane, parallel to the flat radiator, at different distances.	92

4.- EXPERIMENTAL CHARACTERIZATION OF AIRBORNE POWER ULTRASONIC TRANSDUCERS

Fig.4.1.- Impedance analyzer HP 4194A.	96
Fig.4.2.- Bode plot with the determination of the bandwidth of a transducer.	97
Fig.4.3.- Typical σ -n curves.	98
Fig.4.4.- Block diagram of the power electronic system for stability tests.	99
Fig.4.5.- Elements of the stability tests measurement chain.	99
Fig.4.6.- Clean and distorted signals.	101
Fig.4.7.- Relationship between excitation voltage and power.	102
Fig.4.8.- Langevin transducer with two separated ceramic stacks.	103

Fig.4.9.- Example of a 1D frequency sweep around resonance.....	104
Fig.4.10.- Example of a 2D frequency sweep around resonance.....	104
Fig.4.11.- Example of a burst excitation signal.....	105
Fig.4.12.- Block diagram for the experimental modal determination.....	106
Fig.4.13.- Geometric definition of a Langevin transducer for a modal analysis.....	107
Fig.4.14.- Modal spectrum obtained for the Langevin transducer, between 14 and 33 kHz.....	107
Fig.4.15.- Breakdown of the frequency response function.	108
Fig.4.16.- Natural frequencies and mode shape of the Langevin transducer.	109
Fig.4.17.- Block diagram for the ultrasonic field experimental setup.....	110
Fig.4.18.- Semi-anechoic chamber for the experimental ultrasonic field determination. ..	111
Fig.4.19.- Anechoic chamber for the directivity determination of the ultrasonic system. ..	112

5.- DEVELOPMENT OF POWER ULTRASONIC SYSTEMS

Fig. 5.1.- Electrical response of the APUT with stepped-grooved circular radiator.	114
Fig. 5.2.- Power capacity of the stepped-grooved circular plate transducer.	115
Fig. 5.3.- Evolution of temperature with the transducer working continuously with 50 W, 100 W and 200 W supply.	116
Fig. 5.4.- Evolution of resonance frequency with the transducer working continuously with 50 W, 100 W and 200 W supply.....	116
Fig. 5.5.- Measurement of the velocity of vibration with the 1D laser vibrometer.	117
Fig. 5.6.- Relationship between electric current and vibration velocity.	118
Fig. 5.7.- Displacement evolution with voltage.	118
Fig. 5.8.- Wide frequency range response of the APU transducer with 20 V supply.....	119
Fig. 5.9.- 2D sweeps around resonance (vibration velocity).....	120
Fig. 5.10.- 2D sweeps around resonance (current).	120
Fig. 5.11.- Spectra at the resonance frequency of the APUT with circular radiator.....	121
Fig. 5.12.- EMA of the APUT with stepped-grooved circular plate.	122
Fig. 5.13.- ME'Scope model of the APU transducer with circular plate.	123
Fig. 5.14.- Spectral distribution of modal frequencies of the circular plate transducer.....	123
Fig. 5.15.- 7NC operational mode for the circular plate transducer at 25842 Hz.	124
Fig. 5.16.- Closest modes to the operational at 25842 Hz.....	124
Fig. 5.17.- Axis orientation for the experimental determination of the ultrasonic field generated by the APUT with stepped-grooved circular radiator.	125
Fig. 5.18.- Ultrasonic field along the axis of the radiator of the transducer.	126
Fig. 5.19.- 2D ultrasonic field in the plane YZ at different distances from the radiator.....	126
Fig. 5.20.- 2D ultrasonic field in perpendicular planes to the transducer radiation surface.....	127
Fig. 5.21.- Electrical response of the APUT with flat rectangular radiator.....	129
Fig. 5.22.- Power capacity of the flat rectangular plate transducer.	130
Fig. 5.23.- Evolution of temperature with the transducer working continuously with 50 W, 100 W and 200 W supply.	131

Fig. 5.24.- Evolution of resonance frequency with the transducer working continuously with 50 W, 100 W and 200 W supply.....	132
Fig. 5.25.- Measurement of the velocity of vibration with the 1D laser vibrometer.	132
Fig. 5.26.- Relationship between electric current and vibration velocity.....	133
Fig. 5.27.- Relationship between electric voltage and displacements.	133
Fig. 5.28.- Wide frequency range response of the APU transducer with 20 V supply.....	134
Fig. 5.29.- 2D sweeps around resonance (vibration velocity).	135
Fig. 5.30.- 2D sweeps around resonance (current).	136
Fig. 5.31.- Points for the spectrum determination.	136
Fig. 5.32.- Spectra at the resonance frequency.	137
Fig. 5.33.- Experimental modal analysis of the APU transducer with rectangular plate. ..	138
Fig. 5.34.- ME'Scope model of the APU transducer with rectangular plate.	139
Fig. 5.35.- Spectral distribution of modal frequencies of the rectangular plate transducer.....	139
Fig. 5.36.- 12NL operational mode for the rectangular plate transducer at 21130 Hz.	140
Fig. 5.37.- Closest modes to the operational at 21130.....	141
Fig. 5.38.- Ultrasonic field along the axis of the radiator of the transducer.	142
Fig. 5.39.- 2D ultrasonic field in the plane YZ at different distances from the radiator.....	142
Fig. 5.40.- 2D ultrasonic field in the perpendicular planes to the transducer's radiation surface...	143
Fig. 5.41.- Ultrasonic field in the axis normal to the radiating surface.	143
Fig. 5.42.- 2D ultrasonic field in the plane YZ at different distances from the radiator (SWR).	144
Fig. 5.43.- 2D ultrasonic field generated by an ultrasonic SWR in the perpendicular planes to the radiation surface.	144
Fig. 5.44.- Directivity of the two ultrasonic systems.	146
Fig. 5.45.- Vibration of the components of the transducer.....	148
Fig. 5.46.- Operational mode of the transducer at a frequency of 19149 Hz.....	148
Fig. 5.47.- Shape of the adapters for the mechanical amplifier.	149
Fig. 5.48.- Adapters for the experimental analysis.....	150
Fig. 5.49.- Airborne power ultrasonic transducer with circular adapter.....	150
Fig. 5.50.- Impedance analyzer HP 4194A and the transducer with circular adapter.	151
Fig. 5.51.- Temperature measurement points.....	152
Fig. 5.52.- Evolution of temperature along the transducer.....	153
Fig. 5.53.- Temperature with the transducer working with a 20 W supply.....	153
Fig. 5.54.- Location of the displacement measurement point.....	155
Fig. 5.55.- Relationship between supplied voltage and electric power.	155
Fig. 5.56.- Vibration velocity between 1 kHz and 90 kHz of the five configurations.	156
Fig. 5.57.- Vibration velocity between 18.5 kHz and 21.5 kHz of the five configurations.	157
Fig. 5.58.- 2D sweeps around resonance of the five ultrasonic configurations.	159

6.- AIRBORNE POWER ULTRASOUND FOR DRYING PROCESSES INTENSIFICATION AT LOW TEMPERATURE: USE OF A STEPPED-GROOVED PLATE TRANSDUCER

Fig. 6.1.- Representation of the dehydration chamber.	166
Fig. 6.2.- Silica deposit for the adsorption of the humidity in the dehydration chamber....	167
Fig. 6.3.- View of the dehydration chamber from the antechamber.	167
Fig. 6.4.- 2D axisymmetric representation of the model of the drying chamber.	169
Fig. 6.5.- Integrated acoustic pressure (N/m) for each separation between radiator and samples..	169
Fig. 6.6.- Ultrasonic field generated by the stepped circular radiator in the dehydration area.....	170
Fig. 6.7.- Scheme of the measurement chain for the experimental determination of the ultrasonic field generated by the stepped circular radiator inside the drying cabinet.	172
Fig. 6.8.- Frequency behavior of the 1/8" microphone GRAS 40DP.....	173
Fig. 6.9.- System for acoustic measurements.....	173
Fig. 6.10.- Ultrasonic field generated by the stepped circular radiator in the dehydration area.....	174
Fig. 6.11.- Nonlinear effects in the ultrasonic field measured inside the drying cabinet. ..	175
Fig. 6.12.- Determination of the initial moisture content.	177
Fig. 6.13.- Setup for the dehydration experiments.	179
Fig. 6.14.- Apple samples before and after the dehydration process.	183
Fig. 6.15.- Experimental and calculated moisture evolution during drying apple slices (-12 °C)...	184
Fig. 6.16.- Experimental and calculated moisture evolution during drying apple slices (-8 °C)...	186
Fig. 6.17.- Experimental and calculated moisture evolution during drying apple slices (No US)..	188
Fig. 6.18.- Experimental and calculated moisture evolution during drying apple slices (200W). ..	190

ANNEX A.- EFFECTS OF NONLINEAR PHENOMENA CREATED BY POWER ULTRASOUND

Fig. A. 1.- Nonlinear propagation path of a sinusoidal wave of finite amplitude in air at different distances from the source.	201
Fig. A. 2.- Effect of acoustic saturation of an ultrasonic wave in air at 5.7 m from the source.....	202
Fig. A. 3.- Acoustic streaming generated by a travelling wave over a cylindrical container.	204
Fig. A. 4.- Acoustic streaming set up in a sound field: a) travelling wave; b) standing wave.....	204

ANNEX B.- ELECTROMECHANICAL ANALOGIES

Fig. B. 1.- Representation of the electric dipoles of a piezoelectric material.	208
Fig. B. 2.- Commercial piezoelectric ceramics.....	209
Fig. B. 3.- Notation of axes.	210
Fig. B. 4.- Resonant series circuit.	214
Fig. B. 5.- Equivalent circuit for ultrasonic transducers operating near resonance.....	214
Fig. B. 6.- Functional block diagram of the dynamic tuning procedure.....	216

ANNEX C.- SIMULATION OF THE MECHANICAL PRESTRESS IN POWER ULTRASONIC TRANSDUCERS

Fig. C. 1.- 3D model of the vibrator used in the prestress analysis.....	218
Fig. C. 2.- Pretension obtained in the piezoceramic stack.....	218
Fig. C. 3.- Configuration of the stationary solver in the Frequency Domain study.....	219
Fig. C. 4.- Extensional mode of the transducer.	219
Fig. C. 5.- Contribution of the static and dynamic components.	220
Fig. C. 6.- Frequency domain analysis.	220
Fig. C. 7.- Mechanical stress in the transducer.	221
Fig. C. 8.- 2D axisymmetric model of the vibrator used in the prestress analysis.	221
Fig. C. 9.- Application of the boundary load for the mechanical prestress.....	222
Fig. C. 10.- Prestress obtained in the ceramics of a 2D axisymmetric simulation.	222
Fig. C. 11.- Configuration of the physics tree of the Frequency Domain study.	223

ANNEX D.- ADDITIONAL RESULTS OBTAINED IN THE NUMERICAL SIMULATIONS OF AIRBORNE POWER ULTRASONIC TRANSDUCERS

Fig. D. 1.- Eigenmodes of the vibrator tuned at 26 kHz.	225
Fig. D. 2.- Eigenmodes of the stepped-grooved circular radiator.	226
Fig. D. 3.- Eigenmodes of the APUT with stepped-groove circular plate.	227
Fig. D. 4.- Eigenmodes of the vibrator tuned at 21 kHz.	228
Fig. D. 5.- Eigenmodes of the flat rectangular radiator.....	229
Fig. D. 6.- Eigenmodes of the APUT with flat rectangular radiator.....	230

ANNEX F.- DESIGN OF AN ADAPTATIVE MECHANICAL AMPLIFIER FOR RECTANGULAR RADIATORS. TABLES AND FIGURES

Fig. F. 1.- Other undesired modes.....	233
Fig. F. 2.- Evolution of the natural frequencies with the radius of the circular adapter.	234
Fig. F. 3.- Results of the numerical simulation of the transducer with circular adapter.....	235
Fig. F. 4.- Contour of the vibration mode produced by different long adapters	235
Fig. F. 5.- Physical characteristics of the long-rounded adapter.....	236
Fig. F. 6.- Evolution of the natural frequencies with the length of the long-rounded adapter.	236
Fig. F. 7.- Results of the numerical simulation of the transducer with long-rounded adapter.....	237
Fig. F. 8.- Evolution of the natural frequencies with the side length of the squared adapter.....	238
Fig. F. 9.- Results of the numerical simulation of the transducer with squared adapter.....	239
Fig. F. 10.- Contour of the vibration mode produced by a 27x21 mm rectangular adapter.	240
Fig. F. 11.- Evolution of the natural frequencies with the dimensions of the rectangular adapter.	241

Fig. F. 12.- Results of the numerical simulation of the transducer with rectangular adapter.....	243
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ANNEX G.- DESCRIPTION OF THE TWO DYNAMIC CHARACTERIZATION SYSTEMS

Fig. G. 1.- Block diagram of the previous dynamic characterization system.	245
Fig. G. 2.- Block diagram of the new dynamic characterization system.	246
Fig. G. 3.- Components of the generation system for the dynamics characterization system.	247
Fig. G. 4.- Components of the acquisition system of the dynamics characterization system.	247
Fig. G. 5.- Electromechanical analogies.	248
Fig. G. 6.- Equivalent circuit of a transducer under resonance condition.	249
Fig. G. 7.- Measurement of the admittance and virtual compensation of C_0	250
Fig. G. 8.- Comparison between the two systems for the nonlinear dynamic characterization. ...	251

LIST OF TABLES

Table 3.1.- Dimensions of the components of the vibrator tuned at 26 kHz.	53
Table 3.2.- Dimension of the components of the vibrator tuned at 22 kHz.	66
Table 3.3.- Experimental, numerical and theoretical determination of the desired modes of the rectangular plate.	73
Table 3.4.- Convergence analysis of the meshing for the acoustic field simulation	80
Table 5.1.- Electrical properties of the APUT with circular radiator.....	113
Table 5.2.- Stability tests of the APUT with circular radiator.	114
Table 5.3.- Electrical properties of the APUT with flat rectangular radiator.	128
Table 5.4.- Stability tests of the APUT with flat rectangular radiator.....	130
Table 5.5.- Excitation frequencies where the spectrum has been obtained.	137
Table 5.6.- Low power characterization of the transducer with different adapters.....	151
Table 5.7.- Stability tests of the transducer with different adapters.....	154
Table 5.8.- Final results of the ultrasonic system with different adapters.....	160
Table 6.1.- Parameters used for the drying kinetics modelling.	178
Table 6.2.- Freeze drying experiments carried out in the dehydration chamber.....	179
Table 6.3.- Data for the evaluation of the dehydration parameters.	181
Table 6.4.- Data for the analysis of influence of the applied power.....	182
Table 6.5.- Dehydration coefficients by modelling experimental AFD kinetics.	183
Table 6.6.- Data for the analysis of influence of the applied power at -8 °C.	185
Table 6.7.- Dehydration coefficients by modelling experimental AFD kinetics at -8 °C.....	186
Table 6.8.- Data for the analysis of influence of temperature without ultrasounds.	187
Table 6.9.- Dehydration coefficients by modelling experimental AFD kinetics without ultrasounds.	187
Table 6.10.- Data for the analysis of influence of temperature in experiments with an electric supply of 200W.	189
Table 6.11.- Dehydration coefficients (D_e and k) by modelling experimental AFD kinetics with ultrasounds (200W).....	189
Table B. 1.- Properties of typical piezoelectric ceramics.....	212
Table B. 2.- Mechanical and electrical analogies.	214
Table E. 1.- Physical properties for the components of the different transducers.....	231

ABSTRACT

The application of power ultrasonics in several industrial processes has been proved to be beneficial in terms of acceleration of the process with lower energy consumption and an optimal result. Among the industrial processes that can be enhanced using power ultrasound, we can find defoaming, debubbling, particle agglomeration, supercritical CO₂ extraction, or food dehydration, among others.

Focusing on food dehydration, this process consists of transferring the moisture attached to the solid matrix of the food to the external gas media, like air. This mass transfer process is influenced by two parameters: the internal and the external resistance. Internal resistance results from the characteristics of the solid matrix and temperature while external resistance mainly depends on the boundary layer thickness. Currently, convective hot-air drying (CHAD) is one of the most common and widely used drying techniques used to extend the shelf life of food products. However, this is a highly time and energy-consuming thermal process, which also negatively affects the final quality properties of the dehydrated product such as color, texture, flavor, rehydration capacity, the content of vitamins, or other nutrients.

Airborne power ultrasound (APU) application in drying systems may overcome some of the limitations of CHAD by increasing the drying rate or accelerating the process even if it takes place at lower temperatures.

Generally, power ultrasonic energy is used to produce permanent changes in the treated medium. Its use is based on the adequate exploitation of a series of mechanisms activated by the high-intensity ultrasonic waves, such as radiation pressure, acoustic streaming, agitation, instability at the interfaces, and structural diffusion.

Freeze drying (or lyophilization) is a food dehydration operation that involves freezing the products, minimizing the environmental pressure (keeping vacuum) and removing the wet content by sublimation. On the other hand, freeze drying assisted by power ultrasound needs a gas media for the ultrasonic waves to propagate, so, the environmental pressure is in this case atmospheric pressure. Hence, this process is known as lyophilization at atmospheric pressure, or atmospheric freeze drying (AFD).

Nevertheless, food dehydration processes assisted by power ultrasounds need high energy ultrasonic field around the samples are placed. Airborne power ultrasonic transducers (APUT) are the tools capable of generating the high-intensity ultrasonic field.

The generation of high-intensity ultrasonic field carries a series of issues that the transducer needs to solve. These issues are related to the difficulties of ultrasonic propagation through gas media and to the required high-amplitude vibrations of the transducer.

The attenuation of acoustic waves when propagating through a gas media has a quadratic relationship with frequency, so, ultrasonic waves attenuate much faster than acoustic waves with frequencies in the audible range. On the other hand, it is necessary to have a good impedance matching between the ultrasonic transducer and the propagating medium.

An extensive radiator with a certain surface design, and vibrating with high displacements is capable to provide high acoustic energy at the samples, although it carries other consequences to solve like the appearance of undesired nonlinear effects that may affect the performance of the transducer.

The main goal of the development of airborne power ultrasonic transducers with extensive radiators is to guarantee that the system is capable to operate under a high-power regime, generating the required ultrasonic field and without suffering from undesired nonlinear effects.

In this case, a novel ultrasonic technology has been specifically developed to improve AFD processes. The development of this technology has followed the next steps:

- Numerical design.- Using FEM methods, the design of each component has to tune the transducer to vibrate at the desired frequency and with the desired mode. On the other hand, the possibility of modal interaction with other near modes must be discarded in this step.
- Experimental characterization.- After the transducer has been built, it must be tested to confirm that the system is capable to operate under a high-power regime without showing critical nonlinearities.
- Operation.- The last step consists of determining the efficiency of the transducer in the specific process, like food dehydration.

This work deals with these steps of the development of two airborne power ultrasonic transducers with extensive radiator, obtaining a good characterization of both cases, and an enhancement of freeze drying of food samples, for the transducer that has been use for this process. The document has been divided into six chapters, as follows:

- CHAPTER 1 provides a description of fundamentals of power ultrasonics, explaining the general principles of ultrasounds, and with a brief state-of-the-art of industrial applications assisted by power ultrasound, more specifically food dehydration processes.
- CHAPTER 2 focuses on the description of airborne power ultrasonic systems. The nonlinear behaviors of these systems are also presented here, as well as the transducers we will work with.
- CHAPTER 3 deals with the numerical simulation processes of the two systems and the estimation of the generated ultrasonic field for each case.
- CHAPTER 4 describes all the experiments carried out for the full knowledge of each transducer, including the low power characterization, stability tests, nonlinear dynamics characterization, modal analysis, and acoustic measurements in the near and far field. Some examples of other transducers are also included in this chapter.
- CHAPTER 5 is dedicated to the whole development of the transducers that is the full characterization applying the techniques presented in the previous chapter. This chapter

also includes a preliminary design of an adaptive mechanical amplifier to improve the performance of the transducer.

- CHAPTER 6 shows the influence of the application of the APUT with stepped-grooved circular plate in the enhancement of atmospheric freeze-drying (AFD) experiments over apple slices at a laboratory scale.
- CHAPTER 7 summarizes the principal aspects of this work and the gains achieved after the whole development of the two systems.

This work is a first attempt to scale up AFD process by considering a drying chamber with a new airborne power ultrasonic transducer with stepped-grooved circular radiator, capable of accommodating a larger amount of food samples. The APU application with this new system during AFD kinetics of apple slices resulted in an increased drying rate and a reduced drying time.

As a conclusion, the ultrasonically assisted AFD can be an interesting alternative to an expensive and high-demand energy process such as vacuum freeze-drying. What is now required is to increase efforts directed toward scaling up APU application taking into consideration issues such as drying chamber configuration which will improve the ultrasonic efficiency as well as procedures for the mass production of ultrasonic transducers.

So, future research lines would be the industrial scaling of this technology, using ultrasonic systems with circular radiators and ultrasonic systems with flat rectangular radiators and a set of reflectors.

1.- FUNDAMENTALS OF POWER ULTRASONICS

1.1- Introduction

Ultrasound as a branch of sound refers to the generation and application of elastic waves or mechanical oscillations in time and space that are propagating through a material medium at a frequency above the range of human hearing, whose upper limit is considered to be around 20 kHz [1, 2]. The elastic waves need a material medium to propagate through it but, unlike electromagnetic waves, they cannot be transmitted in vacuum conditions [3]. The ultrasonic range covers a very wide frequency range from 20 kHz up to THz's, although in practice it is limited to 100 MHz's. The ultrasonic spectrum can be divided into two zones. Power ultrasound (PU) refers in air, from 20 kHz up to 100 kHz, whereas in liquids spans the frequency range between 20 kHz up to several megahertz. Diagnostic ultrasound frequencies (in liquids) typically range from 1 MHz up to 50 MHz, and it is mainly used for medical and industrial imaging purposes.

Ultrasonic waves have wavelengths in the range of centimeters to nanometers, and are usefully applied across different disciplines such as earth sciences, life sciences, and engineering. Together with the range of frequency, the intensity level of the wave also influences the generation, propagation, and application of ultrasound. Currently, ultrasound is classified into two groups: low-intensity ultrasound and high-intensity ultrasound, also known as signal ultrasound and PU, respectively. Signal ultrasound is used as a mean to investigate and detect the characteristics of the propagation medium, whereas PU is usually used in practice to cause permanent changes in the physical, chemical or biological properties of materials to which it is applied. Generally, PU studies the high-intensity applications ($> 1 \text{ W/cm}^2$) wherein the energy is applied to cause irreversible transformations in processed media. These transformations are based on the effective exploitation of the nonlinear phenomena associated with the propagation of high-amplitude ultrasound waves [4].

1.2- General principles of ultrasound

Ultrasonic frequency. The frequency, f , is the number of cycles completed by a wave per unit of time, and it is related to the wave velocity in the medium c_0 , and the wavelength λ , which is the distance between two equally vibrating points. The period (T_s) is the time required for the wave to complete a cycle, and its inverse the ultrasonic frequency (f) corresponds to the number of cycles per second, and the unit is Hertz (Hz). The relationships between these parameters are presented in Eq. 1. 1.

$$f = \frac{1}{T_s}; \quad \lambda = \frac{c_0}{f} \quad \text{Eq. 1. 1}$$

Speed of ultrasound. It is the distance traveled per unit time by an ultrasound wave as it propagates through an elastic medium [5], and its value depends of the mechanical properties of the medium. In fluids, the analytical expression of the speed can be obtained from Eq.1. 1:

$$c_0 = \sqrt{\frac{K}{\rho_0}} \quad \text{Eq.1. 1}$$

Where K is the stiffness constant and ρ_0 is the density of the medium. In gases the value of the speed of ultrasound depends on the static density of the gas, the static pressure P_0 and the adiabatic index γ , and its value is given by Eq.1. 2 [6]

$$c_0 = \sqrt{\frac{\gamma P_0}{\rho_0}}; \quad \gamma = \frac{C_p}{C_v} \quad \text{Eq.1. 2}$$

The parameters that define the adiabatic index (γ) are the heat capacity at constant pressure (C_p) and at constant volume (C_v).

The propagation of ultrasound waves in solids are more complicated because it is not possible to displace a section of the medium in one direction without producing displacements in other directions [5]. Considering a homogeneous and isotropic solid, both longitudinal and shear waves can propagate at different velocities. In the case of rods whose diameter is smaller than a wavelength of the propagating wave, the longitudinal (or extensional) sound speed can be obtained from Eq.1. 3, where Y_0 represents the Young modulus:

$$c_{solid,bar} = \sqrt{\frac{Y_0}{\rho_0}} \quad \text{Eq.1. 3}$$

In the same way, the corresponding longitudinal velocity in thin plates can be obtained from Eq.1. 4, where σ represents the Poisson ratio:

$$c_{solid,plate} = c_{solid,bar} \sqrt{\frac{1}{(1 - \sigma^2)}} \quad \text{Eq.1. 4}$$

In solids different than rods, and no so thin that vibrate like membranes or thin plates, the elastic theory of solids involves both shear and longitudinal stresses and strains in the medium. Considering this, the velocity of shear and longitudinal waves can be observed in Eq.1. 5 and Eq.1. 6, respectively [5, 7]. In Eq.1. 5, G represents the shear modulus:

$$c_{solid,shear} = \sqrt{\frac{G}{\rho_0}} \quad \text{Eq.1. 5}$$

$$c_{solid,longitudinal} = \sqrt{\frac{Y_0(1 - \sigma)}{\rho_0(1 + \sigma)(1 - 2\sigma)}} \quad \text{Eq.1. 6}$$

Ultrasonic pressure wave. Ultrasonic waves are characterized by the parameters of mechanical or elastic waves. The more relevant effect of PU in a fluid is to impose an ultrasonic pressure (P_a) to the hydrostatic pressure already acting on the medium. Assuming that a progressive and sinusoidal pressure wave travels in the positive x-direction, its analytical expression as a function of time (t) and space (x) is given by Eq.1. 7:

$$P_a(x, t) = P_{ao} \sin(\omega t - kx); \quad \omega = 2\pi f; \quad k = \frac{2\pi}{\lambda} \quad \text{Eq.1. 7}$$

where, P_{ao} is the amplitude of the pressure wave traveling in the positive x-direction, ω denotes the angular frequency and k the wave number. The amplitude of the ultrasonic perturbation is defined as the instantaneous pressure with respect to the equilibrium and is measured in Pascal (Pa). The effective ultrasound pressure, usually shortened to ultrasound pressure, is the RMS value of the instantaneous ultrasound pressures over a time interval at the point under consideration.

The range of values of sound pressure is wide in terms of perturbations with an appreciable effect. Values between mPa to kPa are quite common. A logarithmic scale is useful to deal easily with sound pressure values. The concept of sound pressure level (SPL) is defined according to Eq.1. 8.

$$SPL = 20 \log \left(\frac{p}{2 \cdot 10^{-5}} \right) \quad \text{Eq.1. 8}$$

In the SPL equation, p represents the value of sound pressure, in Pascals. The reference $2 \cdot 10^{-5}$ is related to the minimum value of sound pressure that a perfect ear is capable to perceive, in other words, it represents the hearing threshold. The unit of SPL is decibel (dB).

Although the use of a logarithmic scale when talking about sound pressure is determined basically by the relation between sound and hearing, it is interesting to know the physiological meaning of the exposure to a number of decibels, or the amount of energy involved in such acoustic activity. In following sections, the amount of energy generated by an acoustic system, and its effects on the propagation media will be expressed in terms of sound pressure level (o SPL), even if it is not related directly to human hearing.

When two progressive pressure waves of the same frequency and amplitude propagate in opposing direction in a medium, a standing wave is formed, due to their interaction. In this case, there is no net propagation of energy, because the peak amplitude of the pressure wave at any point in space is constant in time, and the vibrations at different points throughout the wave are in phase. The locations at which the pressure amplitudes are maxima are known as antinodes, whereas the locations at which the pressure amplitudes are minima are known as nodes. The equation of a standing pressure wave is presented in Eq.1. 9

$$P_a(t) = 2P_{a0}\sin(\omega t) \quad \text{Eq.1. 9}$$

Ultrasonic Impedance. In acoustic systems mechanical and acoustical impedances have to be considered because they involve, in general, mechanical vibratory sources with concentrated parameters, emitting or receiving in a continuous medium with distributed parameters. In order to know the radiated power as well as the reaction of the medium on the source, the medium can be characterized by the radiation impedance. It represents the resistance/load of a medium to the propagation of an ultrasound wave, and it is defined as the ratio of ultrasonic pressure (P_a) to the particle velocity (U) at a single frequency. In the case of a plane wave, the ultrasonic impedance can be obtained according to Eq.1. 10.

$$Z_a = \frac{P_a}{U} = \frac{E}{c_0} = \rho_0 c_0; \quad E = \frac{1}{2} \rho_0 U^2 \quad \text{Eq.1. 10}$$

Here, E is the energy density and the quantity $\rho_0 c_0$ is known as the characteristic or specific impedance of the fluid, and for air, the specific impedance is 428 kg/m²s at 0°C and 415 kg/m²s at 20°C.

At an interface, the percentage of wave energy transmitted or reflected depends on the difference in impedance between the two media. This difference determines the mechanical coupling between the emitting surface of the ultrasound source and the irradiated medium. When this difference is large, the percentage of energy reflected will be relevant and the ultrasound effects will be mainly produced at the interface. On the contrary, when the difference is small, a good matching is achieved, and the majority of the energy is transmitted. In this case, the effects of ultrasound take place in the bulk of the medium [8, 9].

Ultrasonic Power. It is the total energy irradiated by an ultrasonic system per unit of time and it is measured in (J/s) or (W). In general, power is a very important process parameter in the field of applications because the greater the power applied in a medium, the higher are the observed ultrasound effects. For that reason, it is convenient to relate the level of applied energy with the size of the considered system, thereby reporting the ultrasonic energy in a relative form. The result of ultrasonic liquid processing is a function of the energy input per volume treated material and expressed in (kW/m³).

The ultrasonic power (W) is the force exerted by the wave over an area ($P_a S$) multiplied by the particle velocity (U), as indicated in Eq.1. 11.

$$W = UP_a S = U^2 Z_a S = P_a^2 \frac{S}{Z_a} \quad \text{Eq.1. 11}$$

Ultrasonic intensity. A more useful measure of energy is the intensity I , which is the amount of energy transmitted in unit time (i.e. the power) normally through unit area of the source and for plane waves is given by Eq.1. 12:

$$I = UP_a = U^2 Z_a = \frac{P_a^2}{Z_a} = \frac{P_{a0}^2}{\rho_0 c_0} \quad \text{Eq.1. 12}$$

Therefore, the intensity is the power output per unit area of the ultrasonic source or transducer, in W/m^2 [10]. As in a perfect standing wave the intensity is zero because there is no net flow of energy but there is energy stored along the standing wave. Another way to express the energy requirements is by means of the energy density E as the energy applied per unit volume expressed in J/m^3 .

In the same way that it was defined the SPL in decibels in Eq.1. 8, it is also very common to measure the levels of intensity in this unit. In this case, the intensity level (IL) in decibels is defined as indicated in Eq.1. 13, where I is the value of the measured intensity in W/m^2 and the corresponding reference value that is 10^{-9} W/m^2 .

$$IL = 10 \log \left(\frac{I}{10^{-12}} \right) \quad \text{Eq.1. 13}$$

Attenuation. During propagation, the amplitude (intensity) of ultrasonic waves decreases exponentially with the distance because the sound absorption in a fluid media has a quadratic relationship with the frequency of the wave. According to chapter 9 of [5], the attenuation coefficient (α) of a sound wave propagating along a viscous fluid is shown in Eq.1. 14:

$$\alpha = \frac{k^2(2\mu + \mu_B)}{2\rho_0 c_0} \quad \text{Eq.1. 14}$$

Here, μ and μ_B represent the dynamic and bulk viscosity, respectively. The wave number is squared in Eq.1. 14, confirming the quadratic relationship between frequency and sound absorption. This means that the attenuation of an acoustic wave increases quadratically with the frequency.

1.3- Power ultrasound industrial applications

As perfectly indicated in [11], macrosonics is a concept that defines the wide field of high-power sonic and ultrasonic applications. These applications take advantage of some effects produced by the acoustic energy that propagates through a medium. For example, processes that take place in liquids are usually based on cavitation effects, while processes that happen in gas media are based on radiation pressure, acoustic streaming and particle velocity (or acoustic saturation). All these processes require high acoustic pressure amplitude. The threshold between low- and high-acoustic pressure amplitude waves can be approximately established for intensity values which depending on the medium vary between 1 kW/m^2 (150 dB) and 10 kW/m^2 (160 dB) [4]

The number of industrial applications that take advantage of the use of power ultrasound is really big. Neppiras, in [12], explained some of them, in which the issues related to the acoustic propagation media were related, considering that “the use of very high energy ultrasonics is therefore practically confined to solids”. Although this statement is partially true, it was proved, later, that the use of power ultrasonics can also be beneficial in applications in gas and liquid media. In [13], Dr. Gallego-Juárez presented a review of the state-of-the-art of industrial applications that take advantage of power ultrasound. This approach was fully extended in [14], where Dr. Gallego-Juárez and Dr. Graff, with the collaboration of the most prestigious experts worldwide, created a digest of the most interesting industrial applications that use high power

ultrasound. The wide field of power ultrasonics (PU) is currently considered as a green emerging technology that offers a great potential for a wide range of processes. It implies a great variety of practical processing systems with characteristics which are dependent on the effect to be exploited.

The Ultrasonic Systems and Technologies Group (USTG) of the CSIC has been a leading group in the development of airborne power ultrasonic transducers to be used in different industrial applications. The work of the research group has been focused on improving the performance of these transducers by minimizing the nonlinear effects and increasing their power capacity. These efforts led the group to take part in numerous research projects to apply this technology in different industrial applications.

1.3.1- Brief historical review of the power ultrasound activities of the USTG of the CSIC

As mentioned, the research work of the USTG has always been related to ultrasound and more specifically to power ultrasound (PU) in gases and multiphase media where it has been a pioneer in exploring new fields of application. Its major contribution to PU has been the design, development and implementation at laboratory and industrial level of this new family of power sonic and ultrasonic generators with extensive stepped-plate radiators for use in gases, liquids and multiphase media. Furthermore the CSIC group has study and developed in such specific media a series of new technologies for application of the ultrasonic energy to environmental treatments (fine particle removal, sludge filtration), food processing (drying, extraction, defoaming) and manufacture (textile washing, debubbling of coating l1yers, pigment dispersion). In addition, the CSIC group has carried out extensive theoretical and experimental studies about the nonlinear acoustic propagation of high-intensity waves in such low density/inhomogeneous media as well as in the metallic and piezoelectric materials constituting the power transducers under high vibrating stresses. Power Ultrasound, which is the field devoted to the use of ultrasonic energy to produce permanent changes in the treated medium, is considered an emerging, environment friendly and energy saving technology. Presently there is a growing interest for the application of power ultrasound in a large variety of operations. It can be attributed to the special characteristics of ultrasonic energy to provide a sustainable and versatile technological alternative for the development of enhanced energy efficient processes. In fact, ultrasonic waves offer a clean mechanical non-ionizing radiation that due to its effectiveness, low instrumental needs compared with other techniques and reduced process time, make their application to be considered a green and sustainable technology.

Until recently, most of the ultrasonic processes have dealt with the treatment of solid and liquid media. To be mentioned plastic and metal welding, machining, metal forming in solids and cleaning, atomization, emulsification and dispersion, degassing and sonochemical reactions in liquids as the current more representative conventional applications of power ultrasound. However, there are other important media, including gases and multiphase media (gas with particles, bubbles or drops in suspension and liquids with gas content or porous solids with liquid inside), to which the application of ultrasonic energy has been notoriously discarded for long time. The reason of such a situation lies in the difficulty to efficiently generate and propagate ultrasound through low density and inhomogeneous media. The creation and development by Prof. Gallego-Juárez [14] of a novel family of power ultrasonic generators with extensive radiating surfaces of stepped profile

has significantly contributed to address this challenge by allowing the implementation, at laboratory, semi-industrial and even industrial scale, of a number of new ultrasound assisted technologies for environmental, food, and manufacturing sectors. The development of these technologies, generally based on the exploitation of the nonlinear effects created by high intensity waves, has been carried out through theoretical and experimental studies in the field of power ultrasound whose results have been collected in a large number of scientific publications. Such results have been used to determine the mechanisms activated by ultrasonic energy in the new processes treated in low density and multiphase media.

A brief description of the main Airborne Power Ultrasound (APU) technologies developed as well as the non-linear effects investigated is given below and wider explanation about their foundations can be found in the publications and patents herein referenced.

1.3.1.1- Environmental processes

The main process that has been developed in this area is fine particle removal.

The presence of suspended airborne particles (especially very fine particles) in the environment is generally undesirable and dangerous. In fact such tiny particles constitute a major health hazard because their ability to penetrate deeply in the respiratory tissues and their long stay in suspension. Therefore it is necessary to deal with them by precipitation of the disperse phase.

Ultrasonic vibrations by agglomeration and precipitation processes might have an important role to play in cutting down the concentration of solid and liquid particles in smokes, mists and exhaust gases in general. CSIC Research Group has been working for a long time in the study of such mechanisms as well as in the development of industrial applications. By using the new power generators he developed and patented a multifrequency acoustic agglomerator that has been tested at semi-industrial scale as a preconditioning system placed upstream of a conventional electrostatic filter.

The important objective for the combination of two systems is to remove micron and submicron - sized particles which usually are not precipitated by the electrostatic filter alone. As a result, reductions in the range of 40-70 % in the micron and submicron size particles over the efficiency of the electrostatic filter were obtained with flow rates of about 2000 m³/h, a power applied of about 1600 W and treatment time of 2-3 seconds. These results represent a significant improvement particularly bearing in mind the very small size of the particles, the narrow gain margin let by the electrostatic filter, the low level of energy applied and the very short treatment time. The work of the USTG in environmental processes produced the following contributions [15-28].

1.3.1.2- Defoaming assisted by power ultrasounds.

Foam is generally an unwanted by-product in industrial processes because it causes difficulties in process control and in equipment operation. A typical example is in the fermentation industry where foam represents one of the biggest problems. The most efficient conventional method for defoaming is the use of chemical anti-foaming agents but they contaminate the product. High-intensity ultrasonic waves represent a clean and efficient procedure to break foam bubbles. A new ultrasonic defoamer based on the use of the stepped-plate power generator has been developed.

Such system has been successfully tested for the control of excess foam produced in fermenting vessels and in other reactors of great dimensions as well as on high-speed canning and bottling lines during the filling operation. The work of the USTG in defoaming produced the following contributions [29-34].

1.3.1.3- Supercritical fluid extraction.

The use of supercritical fluids as extracting agents has been attracting wide interest for years and, in particular, supercritical carbon dioxide is considered nowadays as a very useful solvent in the extraction process because it is non-toxic, recyclable, cheap, relatively inert, and non-flammable. Nevertheless, the process has a slow dynamics. The use of power ultrasound represents an efficient way for enhancing mass transfer processes by radiation pressure, microstreaming and agitation. This new technique has been successfully tested on vegetable oils extraction in a semi-industrial plant constituted by four high-pressure extraction vessels. The results obtained have shown that the kinetics and the extraction yield are enhanced in a range of 30% to 90% depending of the product. The work of the USTG and other research groups in supercritical fluid extraction processes produced the following contributions [35-39].

1.3.1.4- Drying assisted by power ultrasound.

Drying is a method for preserving food. For food drying the two main conventional procedures are hot-air drying and freeze-drying. Hot air drying is a widely used method but it can produce deteriorative changes in the food. Instead, in freeze-drying, where food pieces are first frozen and then sublimates, the product quality is maintained but the process is expensive. High intensity ultrasonic waves can be used for drying food materials. On the basis of the new family of power ultrasonic generators, a new technology for food dehydration has been developed by using two experimental procedures: forced-air drying assisted by air-borne ultrasound and ultrasonic dehydration by applying ultrasound in direct contact with the material. Both techniques have shown to be effective and the quality of the food products was maintained with low energy consumption. The following section is focused on the State-of-the-art in food dehydration assisted by power ultrasound.

1.4- State of the art in ultrasound-assisted food drying

1.4.1- Convective hot-air drying assisted by power ultrasound

1.4.1.1- Forced Air Dehydration Assisted by Airborne Ultrasound

The application of airborne ultrasonic energy for drying materials has been explored for several decades. High-intensity airborne ultrasound introduces pressure variations at gas/liquid interfaces and, therefore, increases the evaporation rate of moisture. Moreover, in a forced air drying system, the air velocity influences the heat and mass transfer. Acoustic energy produces an oscillating velocity effect that can increase the drying rate at stable air velocity. In addition, high-intensity airborne ultrasound causes microstreaming at the interfaces which reduces the diffusion boundary layer, increases mass transfer, and accelerates diffusion. Therefore, the application of airborne acoustic energy can positively contribute to the drying process [40].

The application of the new stepped-plate generator as an airborne ultrasonic radiator, in combination with forced air at different temperatures, is a procedure aiming to efficiently use the synergistic effect of ultrasonic energy. The experimental system designed and constructed for airborne ultrasonic dehydration is shown in Fig.1.1. It mainly consists of a hot-air generator, a stepped-plate power ultrasonic transducer for 20 kHz with the corresponding electronic generator, and a flat plate parallel to the ultrasonic radiator, acting as a reflector for the formation of a standing wave and also as a sample holder. In addition, complementary sets of equipment to measure temperature, air-flow velocity, and weight were used.

Fig.1.1.- Experimental set-up for forced hot air drying assisted by APU

Experimental tests to characterize the system were carried out with vegetable samples: carrot slices of square (12×12 mm) or circular (14 mm in diameter) shape with 2, 4, and 8 mm thickness. The samples were placed in the flat support plate with their upper surface and contour free. Some representative results are presented in Fig.1.2 and Fig.1.3. Fig.1.2 shows the results obtained with forced air at 60, 90, and 115 °C without and with ultrasound (acoustic pressure level applied at 155 dB). In all cases the size of the samples was 12×12 mm² section with 2 mm thickness. As it can be seen, the effect of ultrasonic radiation is significant at low air temperature, and it diminishes when temperature increases. At the highest temperature (115 °C), the ultrasonic effect was negligible. Dehydration curves are expressed in terms of moisture content on a dry basis (weight of water / weight of dry solid). The influence of acoustic pressure level can be observed in Fig.1.3, where the results of tests conducted at higher intensity (acoustic pressure level of 163 dB) are shown. Comparison between both figures shows that the effect of increasing the acoustic pressure by about 8 dB allows the temperature of the air to diminish by 10 °C, with little increase in flow velocity. Other tests were conducted with the same type of samples by increasing air-flow velocity up to 3 m/s. The results obtained showed that at this forced air speed the differences with and without ultrasound are less significant. Similar results were obtained with samples of circular shape and with different thicknesses. From these results, it can be stated that the application of airborne ultrasound is useful in increasing the efficiency of forced-air drying processes. Nevertheless, this improvement seems to be relatively limited, and the use of airborne ultrasound could be restricted to specific products such as heat-sensitive materials and/or to special applications where rapid drying at low temperature is required.

Fig.1.2.- Forced hot-air dehydration kinetics of carrot at 1.3 m/s without and with APU (155 dB)

Fig.1.3.- Forced hot-air dehydration kinetics of carrot at 1.6 m/s without and with APU (163 dB)

1.4.1.2- Direct Contact Ultrasonic Dehydration

The main difficulty in dehydration by airborne ultrasonic radiation is the low penetration of acoustic energy in food material due to the mismatch between the acoustic impedance of air and that of the vegetable. In fact, the effectiveness of energy transfer between these two media very much depends on their acoustic impedances, defined as the product of the density by the sound speed in the material. To increase energy transfer, a new procedure has been developed and tested in which ultrasonic vibration is applied in direct contact with the vegetable samples together with static pressure [41]. Good acoustic impedance matching between the vibrating plate of the transducer and the food material favors the deep penetration of acoustic energy and increases the effectiveness of the process. The vegetable is subjected to high ultrasonic stresses which, due to the rapid series of contractions and expansions, produce a kind of “sponge effect” and a quick migration of moisture through natural channels or other channels created by the wave propagation, resulting in moisture release from the product. In addition, the production of ultrasonic cavitation inside the liquid may help the separation of the moisture strongly attached.

The experimental setup developed for the initial study of this process is presented in Fig.1.4. The samples were placed on the surface of a support plate and the vibrating plate radiator of the transducer was kept in contact with the samples during treatment by applying static pressure. Air flow at 1 m/s and 22 °C together with a suction system was also applied to facilitate the removal of moisture. The dehydration results obtained with circular carrot slices with 2, 4, and 8 mm in thickness and 14 mm in diameter are shown in Fig.1.5. It can be seen that the drying effect was remarkably improved by this process. In fact, the dehydration process is not only quicker and less

energy consuming than forced air drying (with or without airborne ultrasound), but also more powerful: the final moisture content could be less than 1%. In addition, this process, which is basically due to mechanical action, perfectly preserves the quality of the product.

Fig.1.4.- Experimental set-up for dehydration by direct contact ultrasonic vibration

Fig.1.5.- Dehydration kinetics of carrot slices by direct contact ultrasonic vibration (100W) and various flow velocities.

To interpret the experimental study, a mass transfer model was applied. This model is based on the use of the concept of effective diffusivity (D_e), which allows us to describe the diffusion of moisture within the solid matrix of the sample according to Fick's second law [42].

According to this model, the effective water diffusivity coefficient was identified for experiments carried out at operational conditions. Identified D_e in these experiments in apples ranged from $2.93 \times 10^{-08} \text{ m}^2/\text{s}$ without ultrasound to $8.84 \times 10^{-07} \text{ m}^2/\text{s}$ with ultrasound application; and in potatoes it ranged from $2.2 \times 10^{-08} \text{ m}^2/\text{s}$ without ultrasound up to $1.37 \times 10^{-07} \text{ m}^2/\text{s}$ with ultrasound application.

For the extension of the new procedure to industrial applications, a multi-sample dehydration system capable of controlling the parameters of the process was developed by Gallego-Juárez et al. [43]. An example of this system is schematically presented in Fig.1.6. It is constituted by the following parts: (a) treatment chamber; (b) ultrasonic power generator; (c) signals and power conditioner; (d) data acquisition unit; and (e) PC to monitor and control the parameters of the process. The power ultrasonic generator is constituted by a rectangular plate transducer and an electronic unit for driving the transducer.

Fig.1.6.- Scheme of the direct contact multi-sample ultrasonic dehydration system.

The drying process took place in the treatment chamber. The ultrasonic transducer was located at the upper part of the chamber. A parallelepipedal vacuum chamber, where the suction was applied, was fixed parallel to the transducer plate. Its upper porous surface acts as a multi-sample holder, and facilitates the removal of the moisture extracted from the samples. A pressure cylinder pneumatically controlled by a regulator, was fixed at the bottom of the vacuum chamber and permitted the application of a constant force at the interface between transducer and samples. A forced air generator with flow rate and temperature control increased the removal of internal moisture, which was expelled to the lateral surfaces of the samples. The air velocity was controlled by PWM (pulse width modulation) and measured with a hot-wire anemometer in order to work at constant velocity. The temperature of the samples measured with thermocouples, was recorded during the process and stored in a PC.

1.4.1.3- Convective hot-air drying using a cylindrical radiating chamber

A new airborne ultrasonic device was developed and described in previous works [44, 45] by the Power Ultrasonics Group (CSIC, Spain) and its feasibility has been tested in collaboration with the ASPA Group (UPV, Spain). The design was based on the idea of using the drying chamber as the element to irradiate acoustic energy to the material being dried. In this way, no additional elements are needed to apply ultrasound during drying. The system has been found to be very effective at improving the drying rate of different products. Nevertheless, the ultrasonic effects depended on the magnitude of the process variables, such as air velocity and temperature, applied acoustic energy, and product properties. As a consequence, the study of the influence of the process variables on the acoustic application during drying was considered a relevant subject for research. Drying experiments were carried out using an ultrasonic assisted convective dryer (Fig.1.7) [44]. It involves a pilot-scale convective dryer modified to apply ultrasound. It includes an aluminum vibrating cylinder (10, Fig.1.7a) driven by a piezoelectric composite transducer (9, Fig.1.7a). This device was able to generate a high-intensity ultrasonic field in the air medium, reaching an average sound pressure level of 154.3 dB in stagnant air conditions. An impedance matching unit (13, Fig.1.7a) was included to electrically optimize the electric signal generated at

high frequency (15, Fig.1.7a). The most important electrical parameters of the acoustic signal were measured using a digital power meter (14, Fig.1.7a) and logged using an application developed on LabVIEW.

a) Diagram of the ultrasonic assisted dryer

b) Picture of the ultrasonic assisted dryer

Fig.1.7.- Ultrasonic assisted dryer.

Several strategies have been applied to improve the air drying process and, of these, the introduction of alternative energy sources to hot air drying, such as microwave, infrared radiation or PU, should be emphasized [46]. Compared to other technologies, heating is not the main effect linked to the application of power ultrasound in convective drying processes [47]. Power ultrasound brings about mechanical effects both on the gas-solid interfaces and in the material being dried, which may facilitate water removal without introducing a high given amount of thermal energy [45]. Therefore, using power ultrasound either to dry heat sensitive materials [48] or to apply in low-temperature drying processes has great potential. Despite the promising effects linked to applying ultrasound in drying processes, some technical drawbacks have made the full development of ultrasonic drying complicated. The high energy attenuation in gas systems, as well as, the high impedance mismatch between ultrasonic radiators and air makes the acoustic energy transfer more difficult than in liquid media. Several the raw materials were used in order to test the feasibility of air-borne ultrasonic applications on food drying. For that purpose, materials with very different internal structure have been used. Structure has been characterized by macroscopic and microscopic analysis [49, 50] such as density and porosity measurements and SEM and Cryo-SEM observations. Moreover, instrumental texture tests have been performed.

Ultrasonically assisted hot air drying experiments have been performed using cylindrical (CR) ultrasonic radiators driven by piezoelectric transducers working at frequencies close to 22 kHz. This new ultrasonic technology is well described by Riera et al. [46]. Drying tests were carried out in order to evaluate the efficiency of this device, as well as to assess the influence of the most relevant process variables, such as: air velocity (from 0.5 to 10 m/s) and temperature (from 20 to 70 °C), mass load (up to 108 kg/m³) and ultrasonic power applied (up to 37 kW/m³). Diffusion models were used to describe the water transport mechanisms during drying, as well as to quantify the influence of power ultrasound on kinetic parameters.

Fig.1.8.- Drying kinetics of eggplant at 40°C and 1 m/s with different ultrasonic power.

Airborne ultrasound application exhibited a great ability to speed-up air drying processes. Although, both process variables and product structure largely influence on the ultrasonic efficiency. In the case of eggplant drying, reductions of drying time up to 70% were attained. However, lower time reductions have been found for other products: 32% in carrots, 53% in lemon peel, 45% in orange peel and 40% in potatoes. As it is shown in Fig.1.8 [51]., the ultrasonic power applied; defined as the electric power supplied to the ultrasonic transducer for unit of volume in the drying chamber; largely influenced on the drying kinetic [51]. Thus, the higher the ultrasonic power applied, the faster the drying process. From drying kinetics modeling, it was found that ultrasound increased the rate of both internal and external water transport mechanisms. Moreover, significant linear correlations were found between the effective moisture diffusivity and the external mass transport coefficient with the ultrasonic power applied (Fig.1.9) [49]. The slope of the linear relationship may be considered an estimation of the ultrasonic effectiveness on the drying process and in certain way, it could be also linked to the material sensitivity to the mechanical forces generated by the ultrasonic wave. Thereby, it was confirmed that this effectiveness is largely dependent on the product structure. Therefore, the high porous and soft materials, such as lemon and orange peel and eggplant, exhibited a larger ultrasonic effectiveness than the low porous and harder ones, such as potato or carrot (Fig.1.10) [52].

Air temperature is a key factor in convective drying of foodstuffs due to the temperature rise improves drying rate but it could negatively affects quality traits, this being especially relevant for the treatment of heat sensitive materials. Therefore, the influence of temperature was addressed on ultrasound assisted drying. García-Pérez et al. [44] reported that the ultrasonic effect on mass transport makes almost negligible at 70 °C. This fact reflects that the fraction of energy introduced into the medium by ultrasound application at high temperatures is low compared with the available thermal energy. Finally, it should be mentioned that ultrasound affected the structure of the material being dried. Thus, a larger collapse of the eggplant endocarp cells was promoted by the action of ultrasonic waves [50]. Moreover, ultrasound induced the spread of waxy compound on the cuticle surface of orange peel flavedo [53].

Fig.1.9.- Influence of the ultrasonic power on k and De for drying of potato at 40 °C and 1 m/s.

Fig.1.10.- Influence of the hardness of the material being dried on the ultrasonic effectiveness.

1.4.2- Low temperature drying assisted by ultrasound: APU application with cylindrical radiator (CR)

During the last two decades, the Ultrasonic Systems and Technologies Group (USTG) of the CSIC and ASPA Group of the UPV, from Spain, have been working together towards introducing novel systems and methods in food drying technology, specifically in convective hot-air drying (CHAD) and more recently in low temperature drying (LTD) including atmospheric freeze-drying (AFD) processes. From the beginning, APU proved to be an effective, non-toxic and environmentally friendly way to speed up not only the CHAD process, as indicated in this chapter, but also LTD and AFD processes [54-65]. These APU systems have been successfully used to assist drying of different kind of products at laboratory and semi-industrial level.

Fig.1.11.- Representation of the AFD chamber with cylindrical radiator[62].

All the experiments done so far over AFD processes assisted by airborne power ultrasounds have been carried out using an APU transducer with a cylindrical radiator [55, 56, 58]. The AFD experiments were conducted in a convective dryer with air recirculation, temperature, and air velocity control and an ultrasonically activated drying chamber. A schematic layout of this system is presented in Fig.1.11 [62], where elements E and F correspond to the ultrasonic transducer and the cylindrical radiator, respectively. The food samples are placed inside the cavity of the cylinder, using a tree-shaped sample holder.

The APU application, carried out using a cylindrical radiator, is able to produce a high-intensity acoustic field inside the drying chamber. This allows the evaluation of the efficiency of ultrasonic devices at low temperature conditions, as well as to assessing the influence of the most relevant process variables. A number of feasibility studies of APU applications with CR on LTD and AFD processes were carried out during last decade by UPV and CSIC in their convective low temperature drying facilities with different fruits and vegetables. These facilities have been used by different authors to investigate the effect of: (i) ultrasonic power [54-68]; (ii) air velocity [54, 57, 59, 61, 67, 68]; (iii) air temperature [54, 57-61, 66]; (iv) hardness of the material [55]; (v) sample thickness and size [61, 65].

1.4.2.1- Effect of combined ultrasound and LTD/AFD on the kinetics

In general, the application of APU increased the drying rate and reduced drying time: the more power applied, the faster the process. Santacatalina et al. [57] demonstrated the feasibility of

applying APU to enhance the mass transfer rate during LTD of apple cubes. The samples were dried at five different low temperatures from $-10\text{ }^{\circ}\text{C}$ up to 10°C , with an air velocity of 2 m/s , and a relative humidity less than 10%, both without and with ultrasound (20.5 kW/m^3 , corresponding to 50 W of electric excitation power) application. The maximum reduction of the drying time achieved with APU application was of the order of 72%, and occurred when drying was carried out at sublimation conditions. Two years later, Santacatalina et al. [59] continued his studies of drying apple cubes of the same dimensions, at two different temperatures (-10 and $10\text{ }^{\circ}\text{C}$) and at four different ultrasonic powers (0, 25, 50, and 75 W). In this case, the maximum drying time reduction reached was 80.3% at the maximum power applied. In [58], the same author extended these previous studies to analyzed the contribution percentages of the process variables, air temperature (-5 , -10 , and $-15\text{ }^{\circ}\text{C}$), air velocity (1, 2, 4, and 6 m/s) and ultrasound application (0, 25, 50, and 75 W) to the duration of the AFD of apple samples. The authors found that the effect produced by APU application on drying kinetics was more relevant than the effect produced by air temperature and velocity. Hence, this was considered as the key parameter of the drying process.

The enhancement of LTD by using ultrasound was also studied with products other than apples. Thus, Colucci et al. [61] observed in AFD experiments performed with eggplant cubes, that when an ultrasonic power of 25 W was applied, the average diffusivity coefficient increased by 380% compared to results obtained without PU. This result shows the ability of APU application to accelerate the kinetics. On the contrary, variations of air velocity and temperature showed no relevant effects on drying kinetics.

Sample geometry was another process variable studied. Moreno et al. [62] studied the influence of surface/ volume ratio of two apple sample geometries (slabs and cylinders) on APU effects on the kinetics. In the case of cylindrical samples, drying time was reduced by 69% and 88% when APU was applied at 25 and 75 W , respectively. In the case of slab-shaped samples, the application of the same power level reduced the drying time by 82% and 92%, respectively. The greater decrease in the drying time in the slabs was probably due to the lower surface/mass ratio of the slab samples used compared with the cylindrical ones.

Vallespir et al. [64] focused their interest on improving mass transfer by applying freezing pretreatment and ultrasound application on the convective drying of beetroot cubes. The drying time of the sample cubes decreased (36–43%) when ultrasonic power was applied and decreased (55–58%) when samples were frozen before drying with APU application. In addition, APU application during drying induced relevant increases in both effective diffusivity (60–73%) and mass transfer (24–49%) coefficients. Therefore, ultrasound application was suitable for the intensification of the drying kinetics of beetroot. Carrión et al. [63] studied the ultrasound application to enhance the AFD of mushroom slices. The drying experiments, carried out at a constant temperature of $-10\text{ }^{\circ}\text{C}$ and an air velocity of 2 m/s , showed that the values for the effective diffusivity increase significantly up to 280% as the applied ultrasonic power was increased up to 60 W . This implies a reduction of the drying time up to 74%. In general, we can conclude that the low influence of the air velocity on the drying rate and the porous structures that are generated in dried products by sublimation means that APU application represents an interesting technique to significantly increase the drying rate in LTD processes.

1.4.2.2- Effect of combined ultrasound and LTD/AFD on product quality

In 2018, Rodriguez et al. [69] published a very interesting review that summarizes the effects of the APU application on the quality of different products, dried under different operational conditions. These authors state that the APU at LTD and AFD conditions produced an intensification of the drying process, limiting oxidation reactions and maintaining most of the bio compounds intact. Santacatalina et al. [59] studied the influence of LTD conditions on quality parameters of apple cubes. They carried out drying experiments with an air flow of 2m/s, at two different temperatures (10 and -10 °C), without (0W) and with (25, 50, and 75 W) APU application. Their results showed that APU only had a mild impact on the quality attributes studied (rehydration capacity, hardness, total phenolic content, antioxidant capacity and microstructure). Similar results were obtained in the case of eggplant by the same authors [60] In this case, the cubic samples were dried at different air velocities (1, 2, 4, and 6m/s) and temperatures (10, 0 and -10 °C) without (0 W) and with (50 W) APU application. These processing variables did not result in a relevant influence on the hardness of the rehydrated samples. In addition, they observed that the rehydration capacity was only affected by air temperature. Similar results were obtained by Colucci et al. [65] during ultrasound assisted AFD on the antioxidant properties of eggplant samples. The authors evaluated the effect of air velocity (2, 5m/s), drying temperature (-5, -7.5, -10 °C), sample size (cubic samples of 8.8 and 17.6mm side) and APU power applied (0, 25, and 50 W). Although the degradation was greater when processing larger samples, the APU application did not significantly affect the antioxidant content of the product.

Therefore, the results obtained at laboratory scale shows that APU may be considered a promising technology for enhancing the AFD process. It is necessary to study whether or not this influence can be scaled up to an industrial process. In this regard, it is very difficult to achieve big vibrating chambers with the same acoustic behavior as the small cylindrical transducers used in laboratory scale driers. The industrial scalability of this AFD system is limited by the dimensions of the cylinder and the amount of food to be processed. So, in order to design a more scalable system, different configurations have to be analyzed.

Among these configurations we could find the two APU transducers presented in following chapters of this document: an APU transducer with a stepped-grooved circular radiator and an APU transducer with a flat rectangular plate and a system with reflectors.

Hence, the aim of this work is the design, and development of the APU transducers hypothetically suitable for the industrial scaling-up of AFD processes; the integration and testing of these ultrasonic technologies; and the obtainment of the experimental results of their implementation in a pilot scale drier.

This initiative is a first attempt to scale-up the ultrasonically assisted drying system, moving from a cylindrical transducer with small volume drying chambers to an extensive radiator transducer, more appropriate for a belt transport drying system.

2.- AIRBORNE POWER ULTRASONIC SYSTEMS

2.1- Introduction

As mentioned in Chapter 1, the required ultrasonic fields for each industrial application have specific properties. All of them need a high-intensity acoustic field, although the desired pressure distribution differs depending on the specific application. For example, ultrasonic welding or surgery need a high amount of energy focused in a small area, while acoustic agglomeration requires a coherent ultrasonic field.

According to this, we need a tool capable of generating this high-intensity ultrasonic field in a gas media, providing the required pressure distribution. This tool is the airborne power ultrasonic transducer (APUT) with an extensive radiator.

The APUT has to overcome some difficulties related to the nature of the ultrasonic emission and propagation for power applications. These difficulties are the need of a good impedance matching between the transducer and gas media, the generation of vibrations with high displacements in the radiator and the need of a high-intensity ultrasonic field with certain pressure distribution (coherent or focused). The addition of an extensive radiator contributes to the solution of the mentioned issues.

2.2- Description of an airborne power ultrasonic transducer

The discovery of the piezoelectric effect and the development of piezoelectric solutions allowed the use of ultrasonic energy in different industrial fields. Langevin designed and patented the first sandwich-type transducer for industrial applications in water [70-72], for the search of underwater obstacles. This system used the ultrasonic waves to identify submarine objects by measuring the echo produced by those waves after being reflected in the surface of submarine objects.

Since then, many industrial applications have been taken advantages of the ultrasonic energy. Nevertheless, some issues needed to be solved. These issues were related, firstly, to the media where the transducer is working, and then to the shape of vibration of the transducer, that may lead to undesired behaviors. It is important to indicate that the specific design for each industrial application must fulfil the requirements for an effective solution in technical and economic aspects.

The first approach to a piezoelectric transducer for airborne ultrasound was presented in [73]. Here, a flexural vibrating stepped plate was attached to a piezoelectrically excited vibrator. The stepped circular radiator was designed by [74] to obtain a high directional ultrasonic radiation, offering then a good impedance matching to the propagation medium. A subsequent optimization of the airborne ultrasonic transducer was presented in [75], where the stepped circular radiator was extended, and allowed a high-intensity ultrasonic radiation. A deep study of the ultrasonic radiator will be taken in subsection 2.2.3.

Later designs of airborne power ultrasonic transducers confirmed the initial approaches mentioned before, and tried to increase the power capacity and to improve the efficiency of the systems. Two examples of APUT's will be presented in Chapter 2.4.

This kind of transducers has three main components: the Langevin transducer, or sandwich, the mechanical amplifier, or horn (these two components form the ultrasonic vibrator), and the extensive radiator. The basic structure of this system is presented in Fig.2.1.

Fig.2.1.- Basic structure of an airborne power ultrasonic transducer.

2.2.1- Langevin transducer

The Langevin transducer [70-72], also known as sandwich, is the place where the piezoelectric effect takes place. The electric energy is supplied to a stack of piezoelectric ceramics, which react to that energy by analogous mechanical deformations. In the case of an alternating current at a determined frequency, the ceramics will suffer deformations at the same frequency, generating a mechanical vibration. The structure of the Langevin transducer is presented in Fig.2.2, with two different views, a 3D view and a 2D scheme. The different components of the transducer can here be observed, as well as in Fig.2.3.

Fig.2.2.- Scheme of the basic structure of a Langevin type transducer (or sandwich).

Fig.2.3.- Components of a Langevin type transducer.

The simplest form of this kind of transducer is a stack of several discs of piezoelectric ceramic, sandwiched between two metallic masses with a length of $\frac{1}{4}$ wavelength each. Our transducer has two stacks with two piezoelectric ceramics, separated by a brass flange. Between the piezoelectric ceramics we can find the electric terminals, made of a copper-beryllium alloy, where the electric connections are soldered. The electric power is supplied to the transducer through the ceramics, which have a terminal end and a ground end. When building the transducer, it is important that the ceramics are connected in a proper position, joining the terminal ends of each one.

The positive ends of two ceramics are in contact through the CuBe electric terminals, and the ground ends are in the side in contact with other pieces (brass flange and masses). The piezoelectric ceramics used for this transducer are PZT 8 (hard PZT's), which are the most adequate for power ultrasonics (Table B. 1, in Annex B).

Between the two ceramic stacks we find a brass flange. In a correct operation of the transducer, the Langevin sandwich vibrates in a thickness mode, with minimum displacements in its central part, which corresponds to the brass flange. The reason for this flange is to have a grip with minimum vibration, where the external casing and other elements can be fixed. The vibrational behavior in the central flange is crucial in the design of the Langevin transducer. Although a small radial vibration is unavoidable due to the Poisson's effect, the design of the flange has been focused on the minimization of these radial displacements by the application of cuts with different shapes [76]. In [77], a detailed analysis of the vibrational behavior of a Langevin transducer was done, defining its nonlinear characteristics including a modal interaction due to the effect of the radial vibration of the flange, which happened at 42.9 kHz. In this case, a redesign of the diameter of the central flange was enough to eliminate the energy transfer between the transducer tuned mode (at 21.4 kHz) to the flange radial mode (at 42.9 kHz).

The two ends of the transducer are two cylinders made of stainless steel (AISI 420) named back mass and front mass. The following component of the transducer, which is the mechanical amplifier, or horn, is bolted to the front mass, while the back mass corresponds to the end of the whole system. In a normal operation, the Langevin transducer is intended to vibrate in a thickness mode, this is a longitudinal mode, minimizing radial or flexural vibration. This operational vibration mode, obtained numerically in a finite elements method (FEM) software can be observed in Fig.2.4.

Fig.2.4.- Thickness mode of a Langevin transducer.

The determination of the dimensions of the transducer depends on the mechanical properties of each part and on the desired operational frequency, meaning the frequency that excites the thickness mode. The CuBe terminals are 0.5 mm thick, and its behavior can be neglected in the theoretical analysis and in the simulations that will be introduced in following sections. This determination was first presented by Neppiras in [78], and is shown in Eq.2.1, where l represents the thickness of each component and A is the section. The subscripts define the component of each magnitude: subscript c refers to the ceramics and subscript i refers to the back and front masses.

$$\tan\left(\frac{\omega l_c}{c_c}\right) \cdot \tan\left(\frac{\omega l_i}{c_i}\right) = \frac{\rho_c c_c A_c}{\rho_i c_i A_i} \quad \text{Eq.2.1}$$

All the elements of the Langevin transducer are stuck together using a central bolt made of steel (F1250). This central bolt is also responsible for applying a prestress to the Langevin transducer. As Neppiras stated in [78], the ceramics have low tensile strength and they cannot be bonded strongly to the metal stubs or plates needed for coupling into the load. So, a prestress can solve both problems.

The effect of applying prestress in order to avoid fractures in the ceramics when applying high voltage under resonance is perfectly explained in [79, 80]. Here, it is mentioned that, for power ultrasonic applications, the power requirements are often so severe that the tensile strength of the ceramic material cannot take the high mechanical stress involved. This can be remedied by mechanically prestressing the transducer in the axial direction by an amount of prestress about 25 MPa. The effect of prestressing the transducer is also presented visually in Fig.2.5 [79].

Fig.2.5a shows that the maximum permissible tensile stress amplitude T_{cmax} without applying prestress is very low, it is limited by the fatigue strength of the ceramics. On the other hand, when applying a prestress, the stress amplitude may be limited by the fatigue stress of the bolt (Fig.2.5.b) or by losses produced in the system (Fig.2.5.c).

a) Without prestress, T_{cmax} small b) With prestress, $T_{cmax} \approx T_0$ c) With prestress, $T_{cmax} < T_0$
 Fig.2.5.- Fatigue strength T_f , prestress T_0 and maximum permissible stress amplitude T_{cmax} in the center of the transducer.

According to [79], the mechanical prestress may originate changes of the dielectric, electromechanical and mechanical properties of the piezoelectric ceramics. If the value of the prestress is very high, the ceramics may suffer a depolarization and the bolt may break. On the other hand, Arnold studied in [81, 82] the effects of the mechanical prestress in the resonance and anti-resonance frequencies of the transducer. He reached the conclusion that a prestress less than 50 MPa does not yield remarkable changes on the physical characteristics of the ceramics but a small increase of the dielectric coefficient and a slight displacement of the resonance and anti-resonance frequencies to higher values.

According to the recommendations presented in previous research [79, 81, 82], the value of the applied prestress should be high enough to allow high power supply, but not so high that the transducer suffer irreversible changes in its properties. The transducers designed by the Ultrasonic Systems and Technologies Group (USTG), and also those designed as a part of this work, have a value of mechanical prestress of 25 MPa in the piezoelectric ceramics [46].

2.2.2- Mechanical amplifier

The front mass of the Langevin transducer is bolted to the following component, which is the mechanical amplifier or horn. The main goal of this component is to amplify the amplitude of the vibration transmitted by the Langevin transducer through the front mass, and to obtain maximum values of displacement at its tip, where the extensive radiator is bolted.

Merkulov, in [83], was the first to analyze the efficiency of different types of ultrasonic concentrators to obtain large displacement gains. He studied conical, exponential and catenoidal horns (ultrasonic concentrators or velocity transformers), obtaining higher advantages in terms of displacement gain with the catenoidal amplifier. The analysis of conical horns was completed by Ensminger [84], who added a knowledge of mechanical impedances and stresses due to the application of high power. They obtained a similar result in terms of maximum amplification ratio of about 4.6 between the basis and the tip of the amplifier.

On the other hand, Neppiras [12], studied the three shapes of mechanical amplifiers and a fourth shape, the double quarter-wave cylindrical (or stepped) velocity transformer. The distribution of velocities and stresses in the four mechanical amplifiers, as calculated by Neppiras [12], are presented in Fig.2.6, where it can be observed the distribution of velocity (continuous line) and stress (dotted line) in the four situations. The maximum values for the two variables are reached for the double cylindrical horn.

Fig.2.6.- Distribution of velocity and stress in four types of mechanical amplifiers.

Other researchers, like Eisner [85, 86], designed new mechanical amplifiers, with higher ability to withstand large amplitudes than that of this double cylindrical horn. Sherrit [87] designed a novel folded horn for space applications that allowed a volume and mass reduction, of crucial importance in these applications. O'Shea [88] analyzed numerically the behavior of different configurations of a welding horn as a function of the number and dimensional properties of slots placed in this kind of horns. Nevertheless, the stepped horn is the type of mechanical amplifier used in the transducers design by the Ultrasonic Systems and Technologies Group (USTG). The model and a picture of this kind of mechanical amplifier are presented in Fig.2.7.

The horn is composed by two $\frac{1}{4}$ wavelength long cylinders with different sections. The length of the whole element is $\frac{1}{2}$ wavelength of the operational frequency, which is the frequency that excites the thickness mode of the Langevin transducer and an extensional mode of the mechanical amplifier. A minimum displacement, or no displacement, is expected in the joint between the two sections, so here we can find another grip of the transducer.

Neppiras also presented the velocity transformation ratio (R) of this kind of mechanical amplifier [12], which can be observed in Eq.2.2, where $R1$ and $R2$ correspond to the radius of the sections $S1$ and $S2$, respectively:

$$R = \left(\frac{R1^2}{R2^2} \right) \quad \text{Eq.2.2}$$

Fig.2.7.- Double cylindrical mechanical amplifier.

The effect of the mechanical amplifier is shown in Fig.2.8, which represents the displacements along the horn, when it is vibrating in an extensional mode at a frequency about 31798 kHz. This mechanical amplifier has been simulated considering that is made of a titanium alloy. Each section is $\frac{1}{4}$ wavelength and the radiuses are 20 mm the wide part and 7.5 mm the narrow one. This model achieves an amplification ratio of 6.98, obtained numerically, while the theoretical value of this ratio is 7.11.

a) 3D simulation of the extensional vibration of the horn b) Extensional displacement along its axis.
Fig.2.8.- Effect of the mechanical amplifier in the value of the vibration amplitude.

2.2.3- Extensive radiator

As mentioned in [73], the problems of ultrasonic generation in air are mainly due to the low characteristic impedance of the vibrator and high acoustic absorption in air, which limits the acoustic energy available for industrial processes. The addition of an extensive radiator to a classic vibrator, composed by a Langevin transducer and a mechanical amplifier, may minimize these two issues.

The characteristic acoustic impedance of air at a temperature of 20 °C is 415 kg/m²s [5]. The characteristic impedance of a vibrator with a small radiation surface can be obtained in an impedance analyzer and its value is usually much smaller than the characteristic impedance of air. The impedance matching can be achieved by increasing the radiating surface of the transducer because the radiation impedance is proportional to the surface area of the radiator.

On the other hand, ultrasounds are acoustic waves with frequencies higher than the hearing threshold (20 kHz). As indicated in Eq.1. 14, the absorption of the acoustic energy increases quadratically with the frequency, implying a high absorption in the case of ultrasounds. In order to produce the desired effects, the power ultrasonic transducer has to generate a high-intensity ultrasonic field in a gas medium, even if the absorption is also high. The extensive radiator can fulfill this requirement by vibrating with high amplitude and obtaining directional or focused beams for energy concentration [89].

2.2.3.1- Circular piston

The ideal extensive radiator would be a rigid circular piston vibrating with a simple harmonic motion. Here, all the elements of the radiation surface vibrate in phase, at the same frequency and with the same displacement amplitude. The radiation of a piston is perfectly explained in [5]. The acoustic field generated by an ideal circular piston, radiating in free field, is coherent, and presents two different areas, a near field (or Fresnel zone) and a far field (or Fraunhofer zone). The near field shows a pattern of maxima and minima of the value of acoustic intensity. The far field shows a slight decrease of the amplitude of intensity. The intensity (I_0) on the axis of a circular piston with radius a is defined in Eq.2.3. Here, v_0 represents the velocity amplitude on the surface and r is the distance to the radiator. The intensity generated by a piston with radius of 18 cm and radiating in air in a vibration frequency of 21 kHz, can be graphically observed in Fig.2.9.

$$I_0 = 2\rho c v_0^2 \sin^2 \left[\frac{k}{2} (\sqrt{r^2 + a^2} - r) \right] \quad \text{Eq.2.3}$$

Fig.2.9.- Axial acoustic intensity of an ideal circular piston radiating in air.

The limit between near and far field depends on the wavelength and the radius of the circular piston, as shown in Eq.2.4:

$$D = \frac{a^2}{\lambda} = \frac{f a^2}{c} \quad \text{Eq.2.4}$$

According to Eq.2.4, the limit between the Fresnel and the Fraunhofer zones of the proposed example is 1.98 m. The acoustic field generated by this piston is presented in Fig.2.10. This acoustic field has been obtained numerically, by solving the equations proposed by Kinsler for this radiator [5]. The near and the far fields are perfectly distinguishable. The left area corresponds to the near field, with a series of maxima and minima of intensity up to a distance of about 2 m, where a maximum is reached and then a slight but continuous amplitude decrease, which corresponds to the normal behavior of the intensity amplitude in the far field.

Fig.2.10.- 2D acoustic field generated by an ideal circular piston.

Finally, a circular piston shows a directional behavior, depending on its radius and on the wavelength in the propagation medium. The influence of the relationship between the size of the piston and the wavelength is presented in Eq.2.5, that defines the acoustic intensity, in free field, originated by the circular piston in a point situated at a distance r [5]:

$$I = \frac{1}{8} \rho c v_0^2 k^2 a^2 \left(\frac{a}{r} \right)^2 \left[\frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right]^2 \quad \text{Eq.2.5}$$

The directivity pattern of the circular piston can be obtained by applying Eq.2.5, for different sizes and frequencies, as it can be observed in Fig.2.11. The directivity pattern has been numerically obtained using MATLAB for different relationships between a and λ (Fig.2.11.a and Fig.2.11.b), as well as a zoom near the lateral lobes (Fig.2.11.c).

Fig.2.11.- Directivity pattern of a circular piston.

The ideal piston is considered as the reference in the design of extensive radiators because is capable of generating a coherent acoustic field and a very directional directivity pattern.

2.2.3.2- Extensive radiators for ultrasonic transducers

Unlike in ideal pistons, the radiating surface of extensive radiators do not vibrate in phase, with the same amplitude at the same frequency in the whole area, but it vibrates in complex modes, depending on its dimensional and mechanical properties. The radiating plate is bolted to the vibrator at its center, and the vibrator acts as a driving force, transmitting the extensional vibration to the plate, which vibrates flexurally in the mode that corresponds to the excitation frequency.

The first models of ultrasonic transducers with extensive radiators were designed in the late 60's and early 70's of the 20th century. In [74], Barone and Gallego-Juárez, presented a model of a simple piezoelectric ultrasonic transducer with a circular radiator for good impedance matching. This model is presented in Fig.2.12.

Fig.2.12.- Transducer driven by means of a piezoelectric element.

The flat circular plate is driven by the vibrator in an ultrasonic frequency, provoking a vibration in a flexural mode. Depending on the design of the transducer and the plate, this mode could correspond to a simpler mode with a certain number of nodal circles, or a more complex mode with other shapes (nodal circles, diagonals, radial modes, etc....).

A basic analysis of the behavior of a flat circular plate can be done numerically, for a plate, clamped to a rod, which act as a driving force, in its center. Choosing the flexural mode with seven nodal circles (7 NC), see Fig.2.13, for a 2D and a 3D model, we could determine the pressure distribution of the ultrasonic field generated by this flat circular radiator as presented in Fig.2.14.

The ultrasonic field generated by a flat circular plate vibrating in a flexural mode with 7 NC is very different to the field generated by a circular piston, where a coherent ultrasonic field is generated. So, a radiator like this one seems to be no efficient in terms of energy generation.

Fig.2.13.- Operational mode with 7 NC of a flat circular plate.

a) Energy distribution in a 2D central plane.

b) Pressure distribution along the axis of the transducer.

Fig.2.14.- Acoustic field generated by a flat circular radiator vibrating in a 7NC mode.

Knowing that these kind of extensive radiators were not efficient devices for power ultrasonic purposes, researchers tried to find a solution to generate an in-phase radiation. Barone and Gallego-Juárez introduced, in a letter to the editors of the journal *Acustica*, the first modifications to a plate for phase-coherent radiation [90]. Here, the researchers worked with a circular plate, made of duraluminium, clamped to a rod in its center, similar as the one presented in Fig.2.12. The rod and the circular plate were tuned to vibrate in an extensional mode for the first and in a flexural mode with one nodal circle for the second component, at a frequency of 32.5 kHz. They observed that the area inside the nodal circle vibrated in counter phase respect to the area outside the nodal circle. In the nodal circle itself, no vibration was found.

The ultrasonic field generated by the two areas that were vibrating in counter phase was also in counter phase in the propagation media. So, in order to change this behavior and generate a field similar as an ideal piston's, they decided to build steps, with depth of half wavelength in the

propagation medium, in the surface of the radiator, to put the generated ultrasonic waves in phase, as shown in Fig.2.15 [90]:

Fig.2.15.- Modified plate for coherent radiation.

It can be observed in Fig.2.15 how the application of half wavelength deep steps contributes to an in-phase radiation. The sound waves drawn in dotted lines are in phase with the central sound wave. The directivity pattern of this stepped plate was also similar as the directivity pattern of an ideal piston.

This was the first design of stepped radiators for a coherent ultrasonic field. A theoretical study of the frequency of the lowest axisymmetric mode of free vibration of stepped circular plates was done and validated experimentally in [91]. Following works tried to extend this solution to other circular radiators vibrating in higher flexural modes with a number of nodal circles. In [74], the analysis of the behavior of stepped circular plates vibrating flexurally with one, two and three nodal circles, respectively, was presented. The directivity patterns of stepped plates were similar, but not equal, to the directivity pattern of an ideal piston. Also, this work analyzed the behavior of a stepped square plate, offering also a similar performance.

Further improvements on the design of the radiator were focused on the power capacity of the transducers to increase the efficiency of the systems. The power capacity is basically determined by the maximum displacements obtained in the radiating plate, without breaking it. A decisive improvement was presented in [92]. The profile of a new circular radiator (with an operational mode with five nodal circles) was changed by building a 2 mm deep step in the area of the back face covered by the step of the front face, or radiating face. This modification created a grooved profile that allowed a higher power capacity of the system. The denomination of this improved radiator was “stepped-grooved circular plate”.

The grooved profile was also capable of generating a different ultrasonic field. In the study presented in [93], for the development of ultrasonic equipment for industrial defoaming tests, the ultrasonic field generated by the grooved surface was focused on a cylindrical volume located on the axis of the radiator and at a distance of about 33 cm. This means that this grooved profile was able to focus the energy in an area away from the radiator, opening a wide range of industrial applications to be enhanced by the use of the acoustic energy.

As indicated in [94], following the procedure for achieving a coherent radiation, other acoustic field configurations could be achieved. The steps applied on the surface of the plate can act as delays in transducer arrays, depending on the depth of those steps. This provides the opportunity to design, for example, focused fields, as can be seen in Fig.2.16, where the profile of the grooved face of the radiator can be observed, and Fig.2.17 [89], which depicts the focused field generated by that grooved circular plate.

Fig.2.16.- Scheme for the design of focusing radiators.

Fig.2.17.- Acoustic field of a focusing circular plate transducer.

The assembly of the three components described in this chapter and tuned into the desired operational mode composes the ultrasonic systems, capable of producing the desired effects when they are working under certain circumstances.

2.2.4- Macrosonic systems

Further developments were based on the design of macrosonic systems, with the three main components perfectly designed and optimized for high power applications. The first high power ultrasonic transducer for use in gases was presented in [75], and can be observed in Fig.2.18. This optimized system was composed by a simple sandwich with a pair of piezoelectric ceramic rings and steel pieces, followed by a solid horn to amplify the vibration and a stepped circular plate that

working in a flexural mode with three nodal circles. As mentioned before, this is the basic scheme for following systems.

Fig.2.18.- Structure of the first ultrasonic system for high power applications in gases.

One of the most important advances of this transducer is the high mechanical quality factor (Q) reached by these systems. This means that the operational bandwidth is very narrow (about few Hertz's), and that the mechanical impedance may change rapidly.

On the other hand, the mechanical resonance frequency of such systems is subjected to displacements much higher than its bandwidth, due to heating or other physical changes of the transducer.

This implies that high power ultrasonic transducers require an electronic driving system capable of generating at each instant a signal whose frequency is located within that narrow bandwidth and correcting, automatically, the value of this frequency. An electronic system that fulfills these requirements was presented firstly in [95]. This system achieve a dynamic tuning of high Q ultrasonic transducers by keeping constant at its zero value the phase of the motional admittance of the transducer by automatically and instantaneously adjusting the frequency of the driving signal provided by a voltage controlled oscillator.

The whole system for macrosonics, composed by the high power ultrasonic transducer and the electronic system was patented in 1994 [96].

Future designs tried to adapt macrosonic systems for different applications. For example, an array of five stepped-plate transducers for the treatment of large volumes was presented in [97], as well as a transducer with a flat rectangular radiator, and with a set of reflectors where the waves of counter phase were put in phase. The last system had the advantage of using the acoustic energy generated by both sides of the radiator, doubling (almost) its efficiency.

2.3- Nonlinear behavior of a power ultrasonic transducer.

The nature of this type of transducers is to operate in a high power regime. The final objective of these systems is to provoke some effects in samples located in a liquid or gas medium, or in the medium itself. In order to produce the desired effects, a high power ultrasonic transducer has to generate a high-intensity ultrasonic field in the medium. It implies to cover specific requirements

such as good impedance matching between the ultrasonic source and the low-density medium for efficient energy transmission; high directional radiation for energy concentration; high-Q transducers with mechanical amplification for large displacements; and a well-balanced distribution of mechanical stresses in the radiator for operation at maximum power capacity. As mentioned before, the impedance matching can be achieved by increasing the radiating surface of the transducer. On the other hand, the addition of half-wavelength steps in the profile of the plate radiator enables the coherent ultrasonic radiation from an extensive radiator vibrating in a flexural mode.

Finally, the generation of a high-intensity ultrasonic field requires the transducer to vibrate in a tuned operational mode with large displacement, needing a high excitation level. This can result in the transducer vibrating in a nonlinear regime, where undesired nonlinear responses can be excited.

The most basic mechanical model of an ultrasonic system is composed by mass, stiffness, damping and time varying excitation force. If the excitation level is under a certain threshold, the system will behave linearly, but over that threshold, some nonlinearities may appear, causing changes of the resonant frequency, reduced performance of the device and a total failure [98].

Different nonlinear responses are originated by different elements of the transducer and have different effects. Following sections are focused on different nonlinear effects.

2.3.1- Dynamic nonlinear effects.

The nonlinear effects that can be presented in dynamic systems are perfectly explained in [99], and by Mathieson in [100]. Considering a single frequency excitation in a system with one degree of freedom, as could be our transducers working in the desired operational mode, its linear equation of motion can be transformed into the Duffing equation by adding a cubic term to define the nonlinear stiffness (Eq.2.6).

$$\frac{d^2u}{dt^2} + 2\beta\omega \frac{du}{dt} + \omega^2u + \gamma u^3 = q\cos(\Omega t) \quad \text{Eq.2.6}$$

Here, β represents the damping ratio; q and Ω are constants. The nonlinear term (γu^3), where $\gamma \ll 1$, defines the behavior of the system, depending on the value of displacement (u). If the displacement is small, the cubic term can be neglected, and the oscillations of the system are under a linear regime.

If the nonlinear term cannot be neglected, the value of γ determines the nature of this nonlinear effect. If the constant is negative, the natural frequency of the dynamic system moves to lower frequencies, generating a softening effect; while if the value of γ is positive, the natural frequency will move to higher frequencies, generating the hardening effect. These effects can be observed in Fig.2.19 [100].

According also with [100], it has been proved that systems that experience Duffing-like behaviors are prone to experience other nonlinear effects like jump phenomenon and hysteretic behavior. The two effects can be observed in Fig.2.20, which depicts a system showing a softening

behavior, where also jump and hysteretic effects are observed. The jump phenomenon can be observed as a discontinuity between points II and III in the upward frequency displacement, and between points V and VI in the downward displacement. The area comprised between points II, III, V and VI is known as hysteresis region, and is characterized by the fact that there are multiple solutions, and the system is unstable. This may lead even to a chaotic response of the system.

2.3.2- Nonlinear behavior of Langevin transducers.

Dynamic nonlinear effects like frequency shifts and hysteresis are inherent to power ultrasonic devices, and have been widely studied. Nevertheless, there are other consequences from nonlinear behavior, like current and power signal distortions and energy spread resulting in an amplitude saturation effect [101, 102]. The series of experiments carried out by Aurelle [101] proved this distortion in the electric and mechanic variables like current, power and displacement amplitude and how this distortion observed in the time domain was reflected as the appearance of harmonic components in the frequency domain, after applying Fourier transforms. The results obtained after this investigation can be observed in Fig.2.21.

As mentioned before, these ultrasonic systems need a high Q value to be efficient. Nevertheless, when the transducer is driven to high displacements with high velocities, the value of the quality factor is diminished, losing efficiency. The experiments done by Umeda [103] prove the effects of high vibration velocities and temperature increases in the efficiency of ultrasonic transducers, provoking a reduction of the Q factor with increases of the vibration velocity and the temperature.

According to the mentioned works, the appearance of piezoelectric nonlinearities is directly related to a temperature increase in the ceramics. In [104], Uchino carried out a study to determine the influence of the type of electric supply to the transducer. Here, he concluded that a pulse excitation (or burst) was recommended to isolate the effect of high temperatures in the performance of ultrasonic systems. Nevertheless, the use of burst-type excitation has only been achieved successfully in lab based measurements to characterize the nonlinear responses of ultrasonic systems and not for controlling the high-power operating excitation conditions.

The group led by Guyomar analyzed the nonlinear behavior of a Langevin transducer, and proposed a model, obtaining a good agreement with the experimental results [105]. In this work, the dynamic nonlinear effects were also found in the transducer, as a softening effect, and with the appearance of hysteresis and jump phenomena for higher excitation levels. This behavior can be observed in Fig.2.22:

a) Softening effect in the vibration velocity b) Hysteresis in the modulus of the admittance
Fig.2.22.- Nonlinear dynamic behavior of a Langevin transducer.

So, there are some nonlinear effects like dynamic nonlinearities (hysteresis, Duffing-like behavior) and heating that are inherent to the piezoelectric components of the transducer [101, 106], although other components can also suffer from heating, provoking energy losses. Other nonlinear effects related to the harmonic vibration and modes are presented in following paragraphs.

2.3.3- Vibrational nonlinear effects.

Other nonlinear behaviors, such as the appearance of modal interactions, autoparametric behavior, frequency pairs, combination resonances or frequency modulations, as well as multi-modal responses may also be exhibited in ultrasonic devices at high excitation levels, provoking an energy exchange among modes that may generate high amplitude vibrations of the non-tuned modes of the system, causing heating, noise due to the excitation of low frequency modes and component failures [107, 108].

Modal interactions may appear as one or more modal responses at frequencies other than the operating one and tend to result in reduced ultrasonic displacement amplitude at the desired operating resonance frequency, even when the ultrasonic generator is driving only at that. If there are other modes near the operational frequency, it is easier that part of the supplied energy excites those undesired modes. Knowledge of the modal behavior of the system is crucial to determine if it is prone to have interactions between modes.

For example, the nonlinear behavior of a power ultrasonic transducer with stepped circular plate was studied in [109], measuring the vibration velocity in a point of the circular radiator, for a low power excitation, and obtaining a series of eigenmodes in a frequency range around the operational frequency (in this case 25.6 kHz). The modal spectrum obtained after this experimental campaign is presented in Fig.2.23:

Fig.2.23.- Vibration velocity of an APU transducer exposed to a low power excitation.

As it can be observed in Fig.2.23, an amount of eigenmodes may appear around the operational one. Some of those undesired modes may have higher amplitude responses that make it easier to excite when applying high power.

On the other hand, energy leakages can happen when applying high power, transferring part of this energy to other modes whose frequency have any arithmetic relation with the frequency of the working mode. This phenomenon is known as parametric excitation, which takes place in autparametric systems. It can be easily observed in Fig.2.24 and Fig.2.25, that represents the parametric excitation of the transducer analyzed in [109].

As presented in Fig.2.24, for a high power supply, a V-shaped region may appear, in this case, for a downward sweep, originating energy transfer to other modes. The spectra presented in Fig.2.25 show how this energy leakage happens when the excitation is in the V-shaped area of Fig.2.24.b, and not when the excitation is outside this area.

Fig.2.25.b shows that the energy has been transferred to two internal modes, presented in Fig.2.23. The sum of the frequencies of these modes is close to the working frequency.

Fig.2.24.- Normalized vibration velocity frequency responses obtained via upward and downward sweeps around the working frequency.

a) Excitation frequency outside the V-shaped area. b) Excitation frequency inside the V-shaped area
Fig.2.25.- Vibration velocity spectrum measured on the plate for a 300V excitation.

2.4- Airborne power ultrasonic transducers for food dehydration purposes.

2.4.1- Power ultrasonic transducer with stepped-grooved circular plate

The first transducer that is going to be used for lyophilization at atmospheric pressure processes is an airborne power ultrasonic transducer with a stepped-grooved circular plate, radiating from the stepped profile for a coherent acoustic field.

The APUT consists of a piezoelectric Langevin transducer with a stack of four piezoceramic rings sandwiched between two metallic rods under an applied prestress of 25 MPa, a half-wavelength mechanical amplifier to amplify the displacement amplitude and the stepped-grooved circular radiator for a good impedance matching with the gas medium and high amplitude displacements on the surface when applying power. The desired operational mode of the transducer corresponds with an extensional mode of the vibrator which drives the radiator into resonance in a flexural mode with seven nodal circles (7NL). This resonant mode is excited at a frequency close to 25-26 kHz. The plate radiator transducer is shown in Fig.2.26, where it can be observed that the piezoelectrically activated ultrasonic vibrator is attached at the plate center:

This transducer has to be able to generate a high amplitude ultrasonic field, covering a wide area. This implies the need of a coherent ultrasonic field, similar as the one generated by a piston, although it is not equal [110]. When a circular piston vibrates in a harmonic way, all the elements of its surface vibrate in phase, generating a plane wave in the surrounding medium. Nevertheless,

when a circular radiator, driven in its center by a vibrator (or by a shaker), vibrates in a harmonic way, the elements of the surface does not vibrate in phase but the shape of the vibration depends on the excitation frequency and on the modal behavior of the circular radiator, and the acoustic field generated is not a plane wave and it is not coherent.

Fig.2.26.- Airborne power ultrasonic transducer with stepped-grooved circular radiator for food dehydration processes.

As explained in the previous sections, the circular radiator vibrating in an operational mode with seven nodal circles does not generate a coherent field, but it needs the application of half-wavelength deep steps, to generate an in-phase acoustic field, as it can be observed in Fig.2.27.

Fig.2.27.- Half wavelength deep steps applied in a circular plate for coherent radiation.

The Langevin sandwich is composed of two steel cylinders to form the front mass and the back mass. Steel is used because it can withstand the stresses without damage to the internal threads. Four PZT-802 (MTC Electroceramics) ceramic rings are held between the steel masses by a pre-stress bolt. The PZT-802 is chosen due to its high Q_m (≈ 2000) that implies moderate generation of heat, minimizing the appearance of nonlinear effects and internal losses.

The electrodes for the electric insulation and connection of the piezoelectric ceramics of the stack are made of copper-beryllium while the central flange is made of brass as it is a good heat conductor and mechanically resistant to support the case covering the sandwich and mechanical amplifier.

The mechanical amplifier provides sufficient displacement amplitude at the tip, where the plate radiator is attached. It consists of two sections, each of quarter-wavelength, where the amplification depends on the ratio of the cross-sectional areas of the bars. The amplifier is made of a titanium alloy. There are two critical points where failure can occur, one is the union between the amplifier and the plate, consisting of a bolt made of titanium that passes through the plate with a

washer between these two elements and is threaded into the horn, and the other is at the cross-section where the amplifier's diameter changes. Titanium allows high mechanical stresses [111] and has moderate internal losses, high quality factor and high efficiency. The plate radiator is also made of a titanium alloy, because of the same reason: it has a higher elastic limit, and withstands higher displacements than other materials.

The system needs a high efficiency in terms of energy supplied to the surrounding medium with small nonlinear effects. Because of this, the transducer has to generate the ultrasonic energy in a narrow bandwidth and with a high quality factor. This also requires an optimized frequency ultrasonic controller, like the one presented in [95], to keep the system vibrating in the working mode and to avoid it to jump to other undesired modes or to vibrate in an erratic mode.

All the steps carried out with this transducer: theoretical and numerical design; low power characterization; high power dynamics characterization; modal analysis and efficiency in lyophilization processes are properly explained in the following chapters.

2.4.2- Power ultrasonic transducer with flat rectangular plate

A second ultrasonic system to design and manufacture is an APUT with a flat rectangular radiator and an external system of reflectors that allows a coherent radiator covering double area and, also, doubling the efficiency of the system.

This system is an extension of a previous ultrasonic system with reflectors to operate at 9.7 kHz, presented firstly in [97]. This original system can be observed in Fig.2.28.

Fig.2.28.- APU transducer with flat rectangular radiator and a reflectors system.

Conventionally, in order to generate a coherent ultrasonic field from a plate radiator transducer, stepped geometries are incorporated at the nodal lines of the plate, as it happens with circular radiators. The height of each step must be a half-wavelength in the propagating medium. The APU transducer with stepped rectangular radiator has shown modal interaction problems at high power operation [107] and problems due to fatigue [112]. These are probably due to the higher density mode of the stepped rectangular plates. Therefore, the design based on a flat plate radiator with reflectors represents an alternative for power operation with rectangular plates.

To solve this, a system similar as the one presented in Fig.2.28, which is composed of a flat rectangular plate transducer and a stepped reflector structure, can be used. The reflectors form a 45 degrees angle with the two sides of the rectangular plate in order to double the radiating surface of the transducer. In this way, the acoustic energy from both sides of the radiator can be used to obtain the desired effects if a directional or focused acoustic field is reached in the medium, increasing also the electroacoustic efficiency of the system.

The steps are located in the reflector structure instead of in the plate, and the height of the steps depends on the wavelength of the sound in the medium. As shown in Fig.2.29.a, the ultrasonic field generated by both faces of the plate radiator propagates in anti-phase to the stepped reflectors. The alternative addition of steps implies that the waves in phase have to travel half wavelength more than the waves in anti-phase. This fact allows an in-phased ultrasonic field after the reflector system.

a) Description of the generation of a coherent field after reflections in the stepped reflectors. b) Plant view of the airborne power ultrasonic transducer and the reflector system
 Fig.2.29.- Food dehydration system with an APU transducer and a reflectors system.

The structure of this APUT is similar as the one with stepped-grooved circular plate: a piezoelectric Langevin transducer, a half-wavelength mechanical amplifier and the flat rectangular extensive radiator. The desired operational mode of the transducer corresponds with an extensional mode of the vibrator which drives the radiator into resonance in one of its flexural modes. In the present study, the plate radiator vibrates in a flexural mode with twelve nodal lines (12|0). This resonant mode is excited at a frequency close to 21 kHz. The plate radiator transducer is shown in Fig.2.30, where it can be observed that the piezoelectrically activated ultrasonic vibrator is attached at the plate center.

The composition and the materials of each component of the vibrator are also similar as the APUT with circular radiator, but the mechanical amplifier has been lengthened a half-wavelength in the narrow section (Fig.2.29.b) to improve the performance of the whole system of plate radiator transducer and reflectors. The rear face, as well as the front face, of the plate is radiating ultrasonic waves to the reflectors. Therefore, it is possible for the vibrator to interfere with the field between both elements. The operational frequency of the ultrasonic transducer is 21 kHz in air, with a wavelength of 16 mm. The wider section of the mechanical amplifier has a diameter of 40 mm and could therefore produce strong interference in the ultrasonic field generated by the plate. The reason why the narrow section has been lengthened is to keep this wider section outside the

transducer-reflector system. Finally, the rectangular plate radiator is made of duralumin 7075, which offers good quality in a moderate price.

Fig.2.30.- APU transducer with a rectangular plate radiator.

To design an efficient system, the size of the rectangular plate (570x308x34 mm) has to fulfill some requirements. First, the power capacity has to be high to generate a high-intensity ultrasonic field. Also, the covered area of this ultrasonic field must be large enough to place sufficient samples to dehydrate. The length and width of the plate fulfill the requirements, and build a plate with practical size, easy to work with.

Next chapters will be focused on the development, characterization and test of this ultrasonic system composed by an APUT with a flat rectangular radiator and a reflectors system to provide a coherent radiation.

2.5- Conclusion.

Airborne power ultrasonic transducers with extensive radiator have been described in Chapter 2, introducing a brief historical view of the development of each component.

The aim of these systems is to generate a sufficiently high-intensity ultrasonic field to provoke the desired effects in the propagation medium, associated to the industrial applications that benefit from the use of this ultrasonic energy.

The main components of APU transducers are the Langevin transducer, the mechanical amplifier and the extensive radiator. The function of the Langevin transducer is to transform the electric supply into analogous mechanical vibration, operating in a thickness mode; the mechanical amplifier increases the displacement amplitudes at its tip, where the extensive radiator is bolted; and the extensive radiator has to be able to generate a high-intensity ultrasonic field, providing a good impedance matching with the gas medium and providing high acoustic energy due to the high amplitude vibrations of its surface.

Following chapters will be focused on the design, development and characterization of two different APU transducers (with stepped-grooved circular radiator and with flat rectangular radiator), and the application of the APUT with circular plate in freeze drying processes.

3.- NUMERICAL SIMULATION OF ULTRASONIC SYSTEMS

3.1- Introduction

Traditionally, APU transducers were developed by trial and error methods, involving high costs in time and money because each change in the physical characteristics of the transducer implied a new machining and manufacturing.

A theoretical design based on the equations that govern the behavior of each component could act as an initial approach to the design of an efficient system. Nevertheless, the scientific research tried to find a reliable model to ease the whole process.

Finite element method (FEM) is a very reliable tool for modeling and analyzing the behavior of ultrasonic systems. This method is widely used in engineering to solve problems related to structure analysis, heat transfer, dynamics, mass transport and electromagnetism, among others.

As explained in [113], FEM is an approximation method of continuous problems so that the analytical solutions can be obtained, without solving complex systems of differential equations, by discretizing the geometry. The body is divided into a finite number of elements, whose behavior is specified by a number of parameters associated to the nodes, which are joining points with adjacent elements. The solution of the whole system now follows the rules of discrete problems, so that the whole system is composed by the assembly of the elements.

Hence, FEM consists on transform a continuous body into an approximate discrete one. This new equation system leads to approximate solutions, with an error that depends directly on the number of elements in which the geometry is divided. The higher the number of elements, the lower the error and the greater the computational resources required to obtain the solution.

The first time that the concept “finite element method” was used was in 1960, when Clough introduced triangular and rectangular elements in a 2D stress analysis [114]. Works, done in the 70's, already proved the suitability of FEM in the numerical design of complex geometric configurations and piezoelectric devices [115], even the case of sonar transducers [116].

The design of power ultrasonic transducers has also been utterly enhanced by the use of FEM, for example, Kagawa et al [117] applied FEM in the simulation of the behavior of a composite piezoelectric ultrasonic transducer, obtaining a good match between the numerical and the experimental results in terms of electric response of the transducer and acoustic generation. Further down, Jaehwan et al. [118] were capable of optimizing a radiating plate excited by a piezoelectric actuator, using FEM.

The theoretical and numerical design of power ultrasonic transducers is properly explained in [119]. This document focuses on the design of Langevin-type transducers, considering the behavior of the piezoceramic disks and the steel masses separately, and then simulating the whole system.

The use of FEM in the design of full APU transducers, composed by the Langevin sandwich, the mechanical amplifier and the extensive radiator has been published by Riera et al. [46]. This document shows the whole design process of an APU transducer with a cylindrical radiator, including the theoretical design of each component and the numerical characterization of the whole system.

The capabilities of FEM in the design and improvements of APU transducers have also been published [89, 112, 120, 121].

3.2- Fundamentals of the numerical design of an airborne power ultrasonic transducer.

The aim of the numerical design of an airborne power ultrasonic transducer is to have a tuned system, where the three main components (Langevin sandwich, mechanical amplifier and extensive radiator) vibrate in the desired mode at the same frequency. Furthermore, the ultrasonic transducer has to operate efficiently, minimizing the appearance of undesired nonlinear effects when applying high power.

The starting point of a good design is the theoretical study of the components of the transducer: the Langevin sandwich [122, 123], the mechanical amplifier [124], and the extensive radiator [74, 90, 91, 125]. With this basis, a numerical design by FEM is a good tool to obtain an efficient system.

The following sections describe the process of designing an airborne power ultrasonic transducer. This work is focused mainly in two different APUT's, designed under the same basis but with different extensive radiators and working specifications (in terms of operational frequency and mode shape). The two transducers designed, characterized and analyzed in this work have been introduced in the previous chapter, and are the following:

- An APU transducer with a stepped-grooved circular radiator, vibrating in a flexural mode with seven nodal circles at about 26 kHz.
- An APU transducer with a flat rectangular radiator, vibrating in a flexural mode with twelve nodal lines at about 21 kHz, and with a reflector system for a coherent radiation.

3.2.1- General principles of numerical simulation using COMSOL Multiphysics®

The process for the numerical simulation of any geometry to solve any kind of physical situation (heat transfer, flow dynamics, wave propagation...) is similar. Specifically, the numerical simulation of the behavior of airborne power ultrasonic transducers, using the FEM software COMSOL Multiphysics®, must follow several steps: geometric modelling, material assignment, physics determination, meshing, equation solving and presentation of results.

- **Geometric modelling.** The first decision is to choose a space dimension for the simulation. Up to five different space dimensions are available in COMSOL Multiphysics®: 1D, 1D axisymmetric, 2D, 2D axisymmetric and 3D. Power ultrasonic transducers can be studied using 2D axisymmetric or 3D models, depending on its physical geometry. Then, it is

necessary to model the geometry using an editor available in the software or importing models designed in any CAD software.

- **Material assignment.** Each domain of the model has to be assigned a material with the properties related to the physics that include each domain.
- **Physics determination.** The choice of the type of simulation is done in this step. For example, the analysis of the performance of an ultrasonic transducer working at its operational frequency can be carried out with a multiphysics simulation. Here we have to choose two physics: electrostatics for the piezoelectric ceramics and solid mechanics for all the domains. The properties of the materials assigned to each domain have to fulfill the requirements of each physic. The piezoelectric ceramics have to be characterized with the piezoelectric constants and mechanical parameters (Young modulus, Poisson ratio and density), while the rest of elements just need mechanical parameters. All the boundary conditions are also defined here (symmetry, initial values, prescribed displacements, constraints, electric excitation, etc.).
- **Meshing.** After defining all the characteristics and properties of the simulation, we have to define the mesh. This step is crucial for a good performance of the model; a coarse mesh will drag meshing errors and an extremely fine mesh will require high computational cost.
- **Equation solving.** When the model is properly designed and the meshing has been completed, is moment for the definition of the solver. It can be an eigenvalue determination or analysis of the system working in a specific frequency range, a stationary study or time dependent.
- **Presentation of results.** The software COMSOL Multiphysics® is very versatile regarding the possibilities for the presentation of results. It is possible to show noise maps, volumetric representation of deformation of solid, evolution of sound pressure along a line, etc.

3.2.2- Specific process for the simulation of a power ultrasonic transducer using FEM

The numerical design of the two transducers has been done for the vibrator and the plate separately, and then for the final assembly.

As mentioned in previous chapters, the vibrator is composed by the Langevin sandwich and the mechanical amplifier. The classical 1D theory for the design of the Langevin transducer, like the one presented by Neppiras [78] (see Chapter 2.2.1), is useful to determine the thickness mode but it does not consider the lateral vibrations. The 1D theory is sufficiently accurate when the lateral dimensions of the transducer are less than a quarter of the longitudinal wavelength, condition that usually is not fulfilled in high power ultrasonic transducers [120]. For these situations, a different analysis is required.

According to [126], the use of numerical methods is quite accurate if the model, mesh and boundary conditions have been chosen properly. The numerical design of the vibrator, done using COMSOL Multiphysics® involves electrostatics and solid mechanics physics, with a connection between them. In this case, an electric potential defined in the ceramics is transformed into mechanical vibration due to the piezoelectric effect.

The vibrator is composed by the Langevin transducer, with two stacks of two piezoelectric ceramics made of lead zirconate titanate, PZT-8 (see Table B. 1), and back mass and front mass made of steel (AISI 420). On the other hand, the mechanical amplifier is made of a titanium alloy.

The value of the sound speed in the ceramics has been obtained using Eq. B. 9, the sound speed in the front mass and in the back mass has been determined using Eq.1. 5; and for the mechanical amplifier, the equation used corresponds to the longitudinal sound speed in a rod, defined in Eq.1. 3. The properties of the three components are presented in Annex E.

The piezoelectric ceramics used in these transducers are rings with an external diameter of 38.5 mm and internal diameter of 12.8 mm. The area of the piezoelectric ring is 10.35 cm². The thickness of these piezoelectric ceramics is 6.35 mm each. The piezoelectric disks used in these transducers can be observed in Fig. 3.1. Here, it can be seen dots painted in a face of the disks. These dots indicate the face of the ceramic with a positive polarization.

The back and front mass are made of stainless steel AISI 420; they are also rings with an external diameter of 40 mm and internal diameter of 9 mm. So, the initial step is the application of Eq.2.1 to determine the thickness of the back mass and front mass.

Fig. 3.1.- Piezoelectric ceramics for airborne power ultrasonic transducers.

Finally, the mechanical amplifier is designed as two cylinders with a quarter wavelength length each. The diameter of the section with bigger area is 40 mm, and the diameter of the section with smaller area is 7.5 mm.

The length of each section depends on the longitudinal sound speed and the operational frequency. The longitudinal sound speed for titanium bars is presented in Table E. 1 in Annex E (5143 m/s). So, the wavelength of a 26 kHz wave is 198 mm, and the theoretical length of each section of the mechanical amplifier is 49.5 mm. In the case of the transducer vibrating at 22 kHz, this length should be 61 mm. Nevertheless, this is a good approach but not the final design of the horn because the two sections are not ideal bars, there are free spaces for the bolts and a flange between the two sections.

The section of an ultrasonic vibrator can be observed in Fig. 3.2. The dimensions of each component must be defined according the frequency where its extensional mode needs to be.

Fig. 3.2.- Section of an ultrasonic vibrator

The mechanical and piezoelectric properties that define the assigned materials of each element of the vibrator are those indicated in Annex E. The physics involved in the simulation are an electrostatics and a solid mechanics interfaces. The multiphysics effect takes place in the ceramics, which is the place where the electric supply is transformed into analogous mechanical vibrations.

The boundary conditions associated to each physic are the following:

- **Solid Mechanics.** The materials are considered as linear elastic isotropic materials, except the piezoelectric ceramics that are defined as piezoelectric materials.
 - o **Free vibration.** All the external boundaries of the model, except those located in the symmetry axis, are allowed to vibrate freely.
 - o **Boundary Loads.** As explained in Annex C for the simulation of the mechanical prestress, two boundary loads with the same value and opposite direction are defined in the central part of the bolt, to provide a mechanical prestress of about 25 MPa in the ceramics. The boundary loads are only enabled for the stationary simulation that establishes the mechanical prestress.
 - o **Prescribed Displacement.** This simulation needs a constraint to reach convergence. An adequate constraint should be fixing a point that does not move when the system is working at the operational frequency (a node). In this case, the flange is not supposed to displace, at least in the extensional direction (z-direction in 2D simulations) when the transducer is working. A proper constraint could be a prescribed displacement of zero in an interior point of the flange. This constraint is only enabled in the stationary study because the mechanical prestress itself acts as constraint in the eigenfrequency analysis.
- **Electrostatics.** The ceramics are also subjected to the electrostatics interface. They are defined as Charge Conservation, Piezoelectric materials. The boundary conditions are related to the electric behavior of each boundary.

- **Zero Charge.** All the external boundaries of the ceramics are defined as zero charge, meaning that the electric displacement field at these boundaries is zero.
- **Ground.** The ends of the ceramics that are in direct contact to other elements of the transducer, like the brass flange and the masses, are connected to ground, so the voltage there is supposed to be null.
- **Terminal.** The ends of the ceramics that are touching other ceramics are connected to the electric terminal. They receive the electric signal from the generator. Nevertheless, in an eigenfrequency study, the transducer works under a condition of short circuit, with all the terminals connected to the common ground [46]. These boundary conditions are depicted in Fig. 3.3, where the zero charge appears in green, the ground ends are painted in blue and the terminals are highlighted in red.

Fig. 3.3.- Boundary conditions of the electrostatics interface.

Once the physics are properly defined, the next step is to build a mesh that defines the size of the elements in which the model is divided. As mentioned before, the mesh definition is crucial because the smaller the elements the higher the accuracy obtained in the simulation, but also the higher the number of elements and the computational resources that are needed in this case.

This issue is more remarkable in the case of complex 3D models because they need a much higher number of elements. 2D axisymmetric models are a simplification of 3D models that have this axisymmetric geometry, which need many fewer elements and allow smaller size of each.

The software COMSOL permits an automatic definition of the mesh depending on the geometry and on the physics. The only grading allowed to the user is the size of the elements (from extremely fine to extremely coarse). The vibrators are simulated using 2D axisymmetric models, as well as the stepped-grooved circular plate. Although it has a 2D axisymmetric geometry, the circular plate is simulated with a 3D model to find other possible modes without an axisymmetric shape. The rectangular plate needs also a 3D model for the calculations

The first study of the different components of the transducer consists of an eigenfrequency analysis to determine the operational frequency of the transducer (where the thickness mode appears), and if modal interaction may happen with other close modes.

The eigenfrequency study is done in two steps, as indicated in Annex C. The first step corresponds to the stationary study that establishes the mechanical prestress, and the second step corresponds to the eigenfrequency study under short circuit condition, having the results of the stationary step as input data for the simulation.

The second analysis corresponds to a frequency domain analysis around the resonance frequency. This simulation has an initial excitation that can be electrical with a voltage defined in the Terminal node or mechanical if a Prescribed Displacement is assigned to any edge or boundary of the geometry. This analysis can provide information about the expected behavior of the transducer in terms of mechanical displacement amplitudes or stresses due to these displacements, for example.

Next sections will be focused on the design of the two transducers indicated previously.

3.3- Numerical design of an airborne power ultrasonic transducer with stepped-grooved circular plate.

The first transducer to study corresponds to an APUT with a stepped-grooved circular plate that operates in a flexural mode with seven nodal circles (7NC) at about 26 kHz. This transducer has been introduced in Chapter 2.4.1.

3.3.1- Numerical design of the vibrator tuned at 26 kHz

The mechanical and piezoelectric properties of the vibrator, composed by the Langevin transducer and the mechanical amplifier, are those indicated in Table E. 1, in Annex E. The dimensions of each element of the Langevin sandwich, as well as the mechanical amplifier are presented in Table 3.1.

Table 3.1.- Dimensions of the components of the vibrator tuned at 26 kHz.

Magnitude	Value
Radius of the ceramics	19 mm
Thickness of the ceramics	6.35 mm each
Radius of the masses	20 mm
Thickness of the backmass	14 mm
Thickness of the mass	13 mm
Radius of the wide section of the horn	20 mm
Radius of the narrow section of the horn	7.5 mm
Length of the wide section of the horn	40.65 mm
Length of the narrow section of the horn	44.65

3.3.1.1- Eigenfrequency analysis of a vibrator tuned at 26 kHz

This geometry has been studied as indicated in the previous section, defining the Solid Mechanics and Electrostatics physics with the correspondent boundary conditions.

In this case, the mesh of this 2D axisymmetric model has been defined automatically by the physics, using extremely fine size of the elements. The total number of elements defined in this case has been 5193, with an average quality of 0.9672. The histogram with the element quality distribution and the mesh itself are presented in Fig. 3.4.

Fig. 3.4.- Mesh of the vibrator tuned at 26 kHz.

According to the eigenfrequency analysis, the extensional mode of the transducer, corresponding to a thickness mode of the Langevin sandwich and an extensional mode of the mechanical amplifier, has been found at 28492 Hz. This frequency is higher than the desired operational frequency of the whole system around 26 kHz. Nevertheless, the operational mode of the transducer is mainly affected by the bigger and heavier component, which, in this case, is the extensive radiator. Depending on the effect of the load (plate and bolting elements), this design could be adequate for a correct behavior of the whole transducer.

The 2D axisymmetric eigenfrequency analysis can only find modes with axisymmetric shapes. An additional 3D simulation has been done for this analysis to find other modes with non-axisymmetric shapes. A flange mode has been found at 28829 Hz, about 400 Hz away from the extensional mode. This operational mode can be observed in Fig. 3.5, which shows 2D axisymmetric and 3D views, and the other close modes are depicted in Annex D.1.

Fig. 3.6 represents the spectral response of the vibrator between 5 and 40 kHz in terms of displacement, and Fig. 3.7 represents this response in terms of conductance. Here it can be observed that, between 5 and 40 kHz there are three main vibrational modes, with separation of almost 10 kHz between them. The next analysis will be the behavior of the transducer when working at its operational frequency.

Fig. 3.5.- 2D axisymmetric and 3D views of the working mode of the vibrator at 28492 Hz.

Fig. 3.6.- Spectral response of the vibrator in terms of displacement.

Fig. 3.7.- Spectral response of the vibrator in terms of conductance.

3.3.1.2- Frequency domain analysis of the vibrator tuned at 26 kHz

Once the operational mode has been numerically determined, the following step consists on studying the behavior of the system when it is supplied with an electric signal. Even if power ultrasonic transducers show an inherent nonlinear behavior when they are subjected to high values of supplied voltage, the numerical simulations are carried out under the linear regime.

Considering that the nonlinearities experienced by the transducer are more noticeable when the supplied electric power is higher, the estimated supplied voltage is 4 V in the numerical simulations of the vibrator. The numerical model for the frequency domain simulation is similar as the model for eigenfrequencies study. The only difference is the indication of the supplied voltage (in this case 4 V), in the Terminal node under the Electrostatics interface.

This numerical simulation has been carried out for a frequency range around the operational frequency (28492 Hz), between 28200 Hz and 28800 Hz, in steps of 1 Hz. The results obtained from the frequency domain simulations can be analyzed paying attention to different variables and behaviors of the system.

An initial analysis has been done to determine the maximum displacement obtained at the tip of the mechanical amplifier for each frequency of the range studied. The graphic presented in Fig. 3.8 shows the evolution of the maximum displacement in the studied range. The simulated frequency sweep indicates that the maximum displacement at the tip, at 28492 Hz, reaches 11 μm , for a 4 V electric supply.

The evolution of the displacements along the vibrator is presented in Fig. 3.9. The red line describes the displacement obtained along the green line drawn over the 2D axisymmetric representation of the vibrator. There are two displacement nodes, corresponding to the zone around the brass flange and a curved area of the mechanical amplifier. The representation of the vibrator highlights areas with minimum displacements or nodes. Finally, it can be easily

appreciated how the mechanical amplifier reaches a displacement ratio between the basis and the tip around 10.

Fig. 3.8.- Displacement at the tip of the horn around the resonance frequency.

Fig. 3.9.- Displacement along the vibrator.

Following chapters will be focused on the stepped-grooved circular radiator and on the whole system.

3.3.2- Numerical design of the stepped-grooved circular radiator

The extensive radiator is the component of an APU transducer whose mission is to generate the ultrasonic field that will provoke the desired effects in the surrounding medium.

The requirements of a specific acoustic distribution in the near field have to be fulfilled. Certain treatments in the surface of the radiator may change the acoustic distribution to obtain the desired one [74, 89]. In the case of the circular radiator analyzed in this section, steps with a half-wavelength depth are applied in the radiating face, coincident with the vibration nodes of the operational vibration shape (seven nodal circles 7NC). The back face of the radiator has also been treated with the application of grooves that allow a focused field and reduces the total mass of the plate. The profile of the circular radiator is presented in Fig. 3.10, where it can be noticed the half wavelength steps in the radiating face and grooves in the back face.

Fig. 3.10.- Profile of the stepped-grooved circular radiator.

The external radius of the circular plate is 196.8 mm and the internal radius is 5.3 mm. The thickness is variable because steps and a groove are applied at its surface. The maximum thickness is 14.96 mm, near the axis of the plate, and the minimum thickness is 4.81 mm in the area between the grooves applied in the back face and the steps applied in the radiating face.

The depth of the steps applied at the radiating surface have different depths, between 6.6 mm and 3.3 mm. The groove applied in the back face has a depth of 3.21 mm.

The numerical analysis of the circular radiator permits the identification of the operational mode and the presence of other near undesired modes. If these undesired modes are close to the operational one, modal interaction may happen, and energy from the working mode may be transferred to these modes.

The mechanical properties of the elements involved in this simulation are presented in Annex E. The circular plate is made of a Titanium Alloy Ti6Al4V. The longitudinal sound speed of the plate has been calculated using Eq.1. 4.

The numerical determination of the eigenfrequencies needs the Solid Mechanics physics. The properties and boundary conditions of the Solid Mechanics physics have little requirements; only an axial symmetry and a free vibration condition to the rest of the boundaries.

Although the geometry of the circular radiator is axisymmetric, the eigenfrequency analysis must be done with a 3D model because not all the vibration modes have an axisymmetric behavior [126]. This implies a much higher computational cost. The simulation consisted of a quarter of the plate, with the proper definition of the symmetries. The 3D model of the stepped-grooved circular plate is shown in Fig. 3.11, which depicts the full revolution of the model.

Fig. 3.11.- 3D model of the stepped-grooved circular radiator.

The next step is the definition of the mesh for the 3D model. The type of element considered is Free Tetrahedral. This condition supposes a mesh with 131371 elements, with an average quality of 0.6728. A whole view of the mesh can be observed in Fig. 3.12.a, while a detailed view of the edge of the radiator can be seen in Fig. 3.12.b, and the histogram with the quality of the mesh is presented in Fig. 3.12.c.

The operational mode, which corresponds to a flexural mode with 7NC appears at 25808 Hz. This mode can be observed in Fig. 3.13. On the other hand, the numerical simulation identified other natural frequencies with its natural vibration modes. The operational frequency and these other close modes are presented in Annex D.2.

According to the numerical results, there are several complex natural modes located near the operational one at 25808 Hz. Nevertheless, the closest mode is situated 133 Hz away. This separation (higher than 100 Hz) suggests that there will be no modal interaction between these operational modes, even if the separation is near the limit. Because of this conclusion, the numerical analysis of the whole system can be done. Following section corresponds to the analysis of the behavior of the assembly of the vibrator and the radiating plate.

3.3.3- Analysis of the behavior of the whole system

The last simulation corresponds to the whole transducer. In this case, taking advantages of the axisymmetric geometry of the APU transducer and of the operational mode (extensional mode of the vibrator and flexural mode with 7NC of the circular radiator), the numerical analysis of its behavior has been done in a 2D axisymmetric model. This 2D simulation permits a huge reduction of the computational cost of this work.

The geometry of the system is shown in Fig. 3.14, where all its components can be appreciated. The materials assigned to each element of the transducer are those indicated in Table E. 1, in Annex E, for the vibrator and the plate, respectively.

Fig. 3.14.- 2D axisymmetric geometry of the APUT with stepped-grooved circular plate.

The frequency where the operational mode happens will be determined with an eigenfrequency analysis. This first study identifies other 2D axisymmetric modes, but not modes with other geometries. Hence, the 2D axisymmetric simulation has been completed with a 3D simulation to identify other close modes. A frequency domain analysis, simulating an electric voltage supply to the piezoelectric ceramics, and at the operational frequency, will give the information of the behavior of the transducer at its normal operation.

The boundary conditions of the multiphysics simulation are indicated in Chapter 3.2.2.

Once the physics are properly defined, the next step is to build a mesh that defines the size of the elements in which the model is divided. In this case, a physics-controlled mesh with extremely fine elements has been chosen. A total of 12165 elements have been defined, with an average quality of 0.8795 over 1. The final mesh and the histogram showing the quality of the elements of the mesh are presented in Fig. 3.15:

a) Meshing

b) Histogram with the quality of the elements

Fig. 3.15.- Mesh of the APU transducer with stepped-grooved circular radiator.

The first study is the eigenfrequency analysis to determine the operational frequency of the APU transducer. According to this simulation, the operational mode of the transducer happens at 25772 Hz. This mode can be observed in Fig. 3.16. The vibration mode of each component corresponds with the desired ones: an extensional mode of the Langevin transducer and the mechanical amplifier, and a flexural model with seven nodal circles for the circular radiator.

Fig. 3.16.- Operational mode of the APU transducer with stepped-grooved circular radiator.

The 3D approach of the eigenfrequency analysis found other close modes that may affect the performance of the transducer, although the closest one is located more than 120 Hz away. Considering that we expect that the transducer will have a high quality factor, energy transfer to other modes is not expected. Nevertheless, this must be proved experimentally. These close modes can be observed in Annex D.3.

Once the operational mode has been numerically determined, the following step consists on studying the behavior of the system when it is supplied with an electric signal. Even if power ultrasonic transducers show an inherent nonlinear behavior when they are subjected to high values of supplied voltage, the numerical simulations carried out are under the linear regime.

The estimated supplied voltage is 100 V in the numerical simulations of the vibrator. The numerical model for the frequency domain simulation is similar as the model for eigenfrequencies study. The only difference is the indication of the supplied voltage, in the Terminal node under the Electrostatics interface.

The simulation procedure is similar as the previous cases: an initial stationary study to define the mechanical prestress followed by the frequency domain study around resonance where the harmonic perturbation is defined.

This numerical simulation has been carried out for a range of frequencies around the operational one (25772 Hz), in this case between 25752 Hz and 25792 Hz, in steps of 1 Hz.

The results obtained from the frequency domain simulations can be analyzed paying attention to different variables and behaviors of the system. An initial analysis is to determine the maximum displacement obtained at the bolt of the plate for each frequency of the range studied. The graphic presented in Fig. 3.17 shows the evolution of the maximum displacement in the studied range:

Fig. 3.17.- Displacement at the bolt of the plate around the resonance frequency.

The expected displacement at the operational frequency of 25772 Hz, for an electric supply of 100 V is about 3.2 μm .

On the other hand, the frequency domain simulation allows the identification of the displacements distribution along the circular radiator. This distribution is presented in Fig. 3.18. It can be observed how the displacements are not homogeneous along the radius of the plate, but there are areas, corresponding to the nodal circles, without displacements at all, and the maximum amplitudes of these displacements decrease, following a Bessel function.

Fig. 3.18.- Distribution of displacements along the radius of the circular plate.

Finally, this analysis also allows the identification of potential damages due to stress when operating under a high power regime. The system, and more specifically the radiating area, is subjected to high amplitude displacements and high mechanical stresses. The maximum stresses of each component of the transducer are indicated in Table E. 1, in Annex E.

A parametric analysis of stress suffered for each part of the transducer has been done, considering an excitation voltage between 50 V and 350 V, in steps of 25 V. The maximum mechanical stress has been determined in the parts made of titanium (mechanical amplifier, bolt and plate), in the parts made of AISI 420 steel (back and front mass) and in the bolt, made of F1250 steel. The evolution of the mechanical stress suffered by each part, working under the different electric inputs is presented in Fig. 3.19. It can be appreciated how, even for high voltages; the mechanical stresses are far from the elastic limits for the plate and for the bolts. Nevertheless, the validation of this fact has to be done experimentally, forcing the system to work up to this amplitude and even with higher excitations.

As a conclusion, it can be stated that the numerical characterization presents a good ultrasonic system, capable of working in a high power regime, and obtaining high values of displacement with an appropriate distribution for the generation of a coherent ultrasonic field. The numerical determination of the acoustic field and the experimental characterization of the dynamic and acoustic behavior of the system will confirm the suitability of this APU transducer to operate in food dehydration processes under a high power regime.

Fig. 3.19.- Evolution of the mechanical stress suffered by each component.

3.4- Numerical design of an airborne power ultrasonic transducer with flat rectangular plate.

3.4.1- Numerical design of the vibrator operating at 22 kHz

This vibrator, tuned at 22 kHz, will drive a flat rectangular radiator, and a system of reflectors to generate a coherent ultrasonic field. The system of reflectors also allows the use of the acoustic energy generated by the rear face of the plate.

This vibrator, shown in Chapter 2.4.2, has the unusual feature of an extended narrow section of the mechanical amplifier. This is a half wavelength-long extension to minimize the influence of the geometry of the horn in the propagation of the acoustic waves from the flat rectangular plate to the stepped reflectors. The lengthening of half wavelength to the horn keeps maximum displacement amplitude at the tip of the amplifier.

On the other hand, this vibrator will be the driving component of a transducer with a rectangular radiator. This implies that the system is not axisymmetric, even if the vibrator is. The numerical simulation of the vibrator has been then done with a 3D model, following the procedure explained in Chapter 3.2.2.

The properties of the components of the vibrator are the same as the vibrator tuned at 26 kHz (see Chapter 3.2.2 and Table E. 1 in Annex E). The model of this vibrator is shown in Fig. 3.20, where it can be appreciated the extension of the narrow part of the mechanical amplifier.

As well as for the transducer tuned at about 26 kHz, the theoretical analysis is a good approach but not enough to define the geometry of each component, a further numerical analysis has been done to determine the final dimensions of the parts of the vibrator. The final geometry of all the elements of the vibrator, obtained numerically, is presented in Table 3.2.

Fig. 3.20.- 3D model of the vibrator tuned at 21 kHz.

Table 3.2.- Dimension of the components of the vibrator tuned at 22 kHz.

Magnitude	Value
Radius of the ceramics	19 mm
Thickness of the ceramics	6.35 mm each
Radius of the masses	20 mm
Thickness of the masses	19 mm
Radius of the wider section of the horn	20 mm
Radius of the narrower section of the horn	7.5 mm
Length of wider section of the horn	49 mm
Length of narrower section of the horn	172 mm

The physics involved in this simulation are the Solid Mechanics and Electrostatics, with the boundary conditions indicated in Chapter 3.2.2, for a 3D model.

The mesh of this 3D model has been defined using free tetrahedral elements with maximum size of element of 2 mm. The total number of elements defined in this case has been 534609, with an average quality of 0.6623. The histogram with the element quality distribution and the mesh itself are presented in Fig. 3.21:

Fig. 3.21.- Mesh of the vibrator tuned at 22 kHz.

3.4.1.1- Eigenfrequency analysis

The numerical modal analysis has been done over the vibrator in two steps, a stationary study that simulates the effect of the mechanical prestress, and the eigenfrequencies study, in order to find the extensional mode of the vibrator, and the possible existence of other close and undesired modes. According to this, the extensional mode of the transducer happens at 22774 Hz.

This operational mode can be observed in Fig. 3.22. Other natural modes have been found, with a separation with the operational one lower than 1 kHz. The closest mode corresponds to a flange mode. The vibrational shapes of other modes found in this simulation are depicted in Annex D.4. No modal interaction is expected with this vibrator. Nevertheless, the simulation of the whole transducer may provide more information about the behavior of the system.

Fig. 3.22.- Extensional mode of the vibrator at 22774 Hz.

The prominence of the fundamental and other near modes can be represented by simulating the mechanical and electrical response of the vibrator. In this case, the mechanical response can be determined with the displacements at the tip of the mechanical amplifier, as it can be perceived in Fig. 3.23, which represents the spectral response of the vibrator between 5 and 40; and the electric response can be observed in Fig. 3.24, that represents this response in terms of conductance.

Fig. 3.23.- Spectral response of the vibrator in terms of displacement.

Fig. 3.24.- Spectral response of the vibrator in terms of conductance.

3.4.1.2- Frequency domain analysis

The frequency domain analysis has been done under a harmonic electric supply of 4 V at its operational frequency, defined in the model under the “Terminal” node of the “Electrostatics” interface, keeping, like other simulations, an initial stationary step to define the prestress and a second step to define the harmonic perturbation in a frequency range between 22674 Hz and 22900 Hz, in steps of 2 Hz.

The results obtained from the frequency domain simulations can be analyzed paying attention to different variables and behaviors of the system. An initial analysis is to determine the maximum displacement obtained at the tip of the mechanical amplifier for each frequency of the range studied. The graphic presented in Fig. 3.25 shows the evolution of the maximum displacement in the studied range.

The simulated frequency sweep indicates that the maximum displacement at the tip happens at 22774 Hz, with an estimated displacement at the tip about 15 μm .

The evolution of the displacements along the axis of the vibrator is presented in Fig. 3.26. The two displacement nodes, corresponding to the zone around the brass flange and a curved area of the mechanical amplifier, appear in the figure, as well as an additional node corresponding to the extension of the narrow section of the horn. The representation of the vibrator highlights areas with minimum displacements or nodes. Finally, it can be easily appreciated how the tip of the horn obtains maximum values of displacement, reaching displacement amplification about 8.

Fig. 3.25.- Displacement at the tip of the horn around the resonance frequency.

Fig. 3.26.- Displacement along the vibrator.

The design of the rectangular radiator and of the system with reflectors for coherent radiation will be approached in following sections.

3.4.2- Design of the flat rectangular radiator

As mentioned previously, the mission of the extensive radiator is to generate a high-intensity ultrasonic field in the surrounding medium. The ultrasonic systems presented in this chapter will be used to enhance mass transfer processes in lyophilization at atmospheric pressure experiments. This process requires wide action area to be really effective. This implies that the ultrasonic field is not focalized in a specific area, but a wide area must have high acoustic pressure. A coherent ultrasonic field can fulfill this requirement.

The flat rectangular radiator, vibrating in an operational mode corresponding to a flexural mode with twelve nodal lines (12NL), is not capable of generating a coherent field, but a system with stepped reflectors will be added to get a coherent field, doubling the radiating surface and obtaining higher acoustic energy.

The numerical analysis of the flat rectangular radiator permits the identification of the operational mode and the presence of other near undesired modes. If these undesired modes are very close to the operational one, modal interaction may happen, and energy from the working mode may be transferred to these modes.

The rectangular geometry of the plate needs 3D simulations to study the behavior of this transducer. Depending on the size of the model, half or even a quarter of the geometry has been analyzed, applying the required symmetry conditions in the proper boundaries. The profile of the flat rectangular radiator is presented in Fig. 3.27.

Fig. 3.27.- Model of the flat rectangular radiator.

The plate has the dimensions shown in Fig. 3.27, which are 570x308x34 mm; and its operational mode consists of a flexural mode with 12 nodal lines 12|0 (12 NL) in the transversal direction ($m=12, n=0$). The plate is considered to be orthotropic ($Y_x=Y_y \neq Y_z; \sigma_x=\sigma_y \neq \sigma_z$), and is made of an aluminum alloy, whose mechanical properties are presented in Table E. 1 in Annex E.

3.4.2.1- Theoretical approach to the vibration of rectangular plates

The theoretical analysis of free vibration of rectangular plates has been widely studied in the past. Works of Warburton [127] or Leissa [128], among others, ended with the determination of an equation for the vibration of rectangular plates, published by W.G. Caldersmith [125] (Eq.3.1):

$$f_{m,n}^2 = \frac{h^2}{4.86\rho} \left[\frac{D_x}{L_x^4} \left(\frac{2m-1}{2} \right)^4 + \frac{D_y}{L_y^4} \left(\frac{2n-1}{2} \right)^4 \right] + m^2 n^2 f_{1,1}^2 \quad \text{Eq.3.1}$$

Where $f_{m,n}$ is the frequency where the desired mode happens; m and n are the number of nodal lines perpendicular to x and y side, respectively; L_x , L_y and h are the length of x and y sides, and the thickness, respectively; ρ is the density of the plate material; $f_{1,1}$ is the first shear mode; and D_x and D_y are the corrected Young Modulus for dimensions x and y , following the expression in Eq.3.2, where Y_x and Y_y corresponds to the Young modulus in x and y directions, and σ_x and σ_y are the Poisson ratios in both directions:

$$D_x = \frac{Y_x}{1 - \sigma_x \sigma_y} \quad D_y = \frac{Y_y}{1 - \sigma_x \sigma_y} \quad \text{Eq.3.2}$$

The previous expression has been proved to have a good matching in rectangular thin plates, but its performance is different when it is applied to thick rectangular plates. In the following paragraphs, a theoretical and numerical analysis of vibration of a rectangular plate is presented.

There are different typologies, with different dimensions, of rectangular plates depending on the specific industrial application. It is not easy to assure that a plate is or not a thin plate, so a FEM analysis is useful. The theoretical and numerical analysis of the vibration of a rectangular plate with dimensions 570x308x34 mm and an operational mode of 12 nodal lines 12|0 (12 NL) in the transversal direction ($m=12$, $n=0$) has been done. The plate is considered to be orthotropic ($Y_x=Y_y \neq Y_z$; $\sigma_x=\sigma_y \neq \sigma_z$), and is made of duralumin, whose mechanical properties are presented in Annex E.

The eigenfrequency that excites the mode with 12NL has been determined theoretically applying Eq.3.1, and the value of $m=12$ and $n=0$. The theoretical result indicates that the desired mode is excited at a frequency of 33789 Hz.

In order to check the suitability of this method, a numerical study, using the FEM software COMSOL Multiphysics®, has been done for the rectangular plate considered, trying to find this operational mode and other near modes.

The determination of the eigenfrequencies of the plate has been done in a 3D numerical model using the Structural Mechanics module, considering the rectangular plate as an orthotropic solid with the mechanical properties indicated in Annex E.

The operational mode with 12 NL is presented in Fig. 3.28, and found at 21158 Hz, which represents a difference of around 12.6 kHz (37%) with the theoretical result.

In order to determine the nature of this error, the extended study tries to identify other modes using both methods.

The input parameters have been normalized establishing a relationship between the length, thickness and number of nodal lines in the plate. In this case, the new parameter is h/d , which is the ratio between the thickness (h) and the distance between nodal lines (d). The results obtained after this new study has been summarized in Fig. 3.29, where it can be observed how the

difference between the theoretical and numerical studies increases linearly with the parameter h/d , meaning that this error is bigger in higher modes or even when the distance between nodal lines is smaller.

Fig. 3.28.- Operational mode with 12 NL of the rectangular plate.

Fig. 3.29.- Accuracy of the theoretical study of vibration of a rectangular plate.

Considering an error of 10% between the theoretical and the numerical studies as acceptable, the parameter h/d should not be higher than 0.18. This means that the theoretical study is accurate when the distance between nodal lines is, at least 5.5 times the thickness of the plate.

This rectangular plate, vibrating in a mode with 12 NL cannot be considered as a thin plate because the distance between nodal lines is 47 mm, not fulfilling the previous requirement. Taking into account that the differences between theoretical and experimental results show a linear behavior in relation to thickness and distance between nodal lines, a correction factor of the Eq.3.1 can be determined. The corrected equation for m nodal lines ($n=0$) is presented in Eq.3.3:

$$f'_{m,0} = f_{m,0} \left(1 - 0.5 \frac{h}{d} \right), \quad \text{where } d = \frac{L_x}{m} \quad \text{Eq.3.3}$$

Where $f_{m,0}$ is the result of the Caldersmith equation. The relation between the corrected theoretical method and the numerical method is shown in Fig. 3.30, where the difference observed between the experimental method and the corrected equation is less than 5% in all cases.

Fig. 3.30.- Accuracy of the corrected equation of the vibration of a rectangular plate.

These results have been obtained applying numerical methods. Nevertheless, an experimental modal analysis of the plate has been also done, obtaining the vibration displacements in the plate with 3D laser vibrometer and processing the results with the software ME'Scope. The measurement setup and the results obtained are presented in the Chapter 5. The operational mode with 12 nodal lines was identified at 21130 Hz, while the numerical simulation found it at 21158 Hz, less than 30 Hz away.

Other modes of interest have been also identified experimentally. The frequencies at which each mode shape happens are close to the numerical simulation, with differences less than 1% in all cases. Table 3.3 shows the results obtained with the three methods for five modes studied in this work (modes with 6, 8, 10, 12 and 14 nodal lines in the transversal direction):

Table 3.3.- Experimental, numerical and theoretical determination of the desired modes of the rectangular plate.

Mode shape	Experimental result (Hz)	Numerical solution (Hz)	Theoretical value (Hz)
6 0	6430	6495	7732
8 0	10950	10974	14373
10 0	15890	15927	23059
12 0	21130	21158	33789
14 0	26480	26459	46563

The results obtained by experimental means and presented in Table 3.3 validate the COMSOL Multiphysics® model used for rectangular plates.

This process has been also proved for other two different rectangular plates: a rectangular plate presented in [129] with a flexural mode with 8 NL (8|0; and another plate introduced in [130], where the rectangular radiator vibrates in a flexural mode with 2 NL (0|2). In these situations, the flexural modes are always parallel nodal lines. This means that the value of m or n is null, and the last term of Eq.3.1 is neglected in this analysis.

As a conclusion, the definition of a thin rectangular plate for the use of the equation proposed by W.G. Caldersmith depends mainly on the thickness of the plate and the chosen mode. The relation between the distance between nodal lines and the thickness of the plate indicates the accuracy of the Caldersmith equation. If the distance between nodal lines is about 5.5 times the thickness, the plate can be considered as a thin plate and the maximum error of the equation is 10% of the value of the frequency at which the desired mode happens.

For the case of thicker plates or plates with higher flexural modes with a number of parallel nodal lines in its operational mode, where the proposed relation is not accomplished, the Caldersmith equation has been adapted, in order to be used with minimum errors.

3.4.2.2- Numerical analysis of the flat rectangular plates

The numerical analysis of the behavior of the flat rectangular plate tries to identify the operational mode by carrying out an eigenfrequency analysis. This study, focused on the flat rectangular plate, has been done using the Solid Mechanics physics, defining simple boundary conditions, which are free vibration in all the boundaries of the plate.

The mesh defined for the sole plate is composed by periodic elements, in this case hexahedral elements, with a maximum size of 7.5 mm, to have at least four elements along the smaller dimension of the plate (thickness). This mesh has 15580 elements with maximum quality (1). This can be observed in Fig. 3.31:

Fig. 3.31.- Mesh of the flat rectangular radiator.

As indicated also in the previous section, the operational mode, which corresponds to a flexural mode with 12NL appears at 21158 Hz. This mode can be observed in Fig. 3.28. On the other hand, the numerical simulation identified other natural frequencies with its natural vibration modes. These other close modes are presented in Annex D.5.

According to the numerical results, there are a number of complex natural modes located near the operational one at 21158 Hz, being the closest one only 116 Hz away. This separation suggests that there might be modal interaction between these operational modes. Nevertheless, the numerical analysis of the whole system will show more accurate information of the APU transducer with this radiator. Following section corresponds to the analysis of the behavior of the assembly of the vibrator and the radiating plate.

3.4.3- Analysis of the behavior of the whole system

The geometry of the system, composed by the vibrator and the rectangular radiator studied in previous sections, is shown in Fig. 3.32, where all its components can be appreciated. The materials assigned to each element of the transducer are the same as those indicated in Table E. 1, in Annex E.

Fig. 3.32.- 3D geometry of the APU transducer with flat rectangular plate.

The frequency where the operational mode happens, and the appearance of other near modes, will be determined with an eigenfrequency analysis. A frequency domain analysis, simulating an electric voltage supply to the piezoelectric ceramics, and at the operational frequency, will give the information of the behavior of the transducer at its normal operation.

A multiphysics study is necessary in this case. The physics involved in this simulation are an electrostatics and a solid mechanics interfaces, with the boundary conditions indicated in Chapter 3.2.2.

The mesh has been defined with free tetrahedral elements whose maximum size has been 10 mm in the plate and 5 mm in the vibrator and the rest of elements. A total of 885037 elements have been defined, with an average quality of 0.6768 over 1. The final mesh and the histogram showing the quality of the elements of the mesh are presented in Fig. 3.33.

a) Meshing

b) Histogram with the quality of the elements

Fig. 3.33.- Mesh of the APU transducer flat rectangular radiator.

The first study is the eigenfrequency analysis to determine the operational frequency of the APU transducer. According to this simulation, the operational mode of the transducer happens at 21049 Hz. This mode can be observed in Fig. 3.34.

Fig. 3.34.- Operational mode of the APU transducer with flat rectangular radiator.

The frequency domain simulation, considering a supplied voltage of 100 V, has been carried out for a frequency range around resonance (21049 Hz). The frequency range under study starts at 20949 Hz and reaches 21149 Hz, in steps of 2 Hz.

The results obtained from the frequency domain simulations can be analyzed paying attention to different variables and behaviors of the system. An initial analysis is to determine the maximum displacement obtained at the plate for each frequency of the range studied. The graphic presented in Fig. 3.35 shows the evolution of the maximum displacement in the studied range.

Fig. 3.35.- Displacement obtained in the plate around the resonance frequency.

The expected displacement at the operational frequency of 21049 Hz, for an electric supply of 100 V is about 3.9 μm .

On the other hand, the frequency domain simulation allows the identification of the displacement distribution along the rectangular plate. The presented evolution corresponds to the displacement along a central line parallel to the long side of the radiator, presented in Fig. 3.36.a. This distribution is presented in Fig. 3.36.b. It can be observed how the values of the maximum and minimum displacements are not equal, but they are similar. The displacements obtained here are more homogeneous than those obtained with the circular radiator (see Fig. 3.18).

Finally, this analysis also allows the identification of potential damages due to stress when operating under a high-power regime. The system, and more specifically the radiating area, is subjected to high amplitude displacements and high mechanical stresses.

Fig. 3.36.- Distribution of displacements along the rectangular plate.

A parametric analysis of stress suffered for each part of the transducer has been done, considering an excitation voltage between 25 V and 350 V, in steps of 25 V. The maximum mechanical stress has been determined in the parts made of an aluminum alloy (plate), titanium (mechanical amplifier, bolt), in the parts made of AISI 420 steel (back and front mass) and in the bolt, made of F1250 steel. The evolution of the mechanical stress suffered by each part, working under the different electric inputs is presented in Fig. 3.37. It can be appreciated how, even for high voltages; the mechanical stresses don't overcome the elastic limits in any case. The maximum stresses are perceived in the parts made of titanium, more specifically, in the bolt that passes

through the plate and is bolted to the mechanical amplifier. This is the area that experiences the higher stresses due to the displacements obtained here.

As a conclusion, it can be stated that the numerical characterization presents a good ultrasonic system, capable of working in a high-power regime, and obtaining high values of displacement without overcoming the elastic limits of the materials. The numerical determination of the acoustic field generated by this transducer together with a reflector system and the experimental characterization of the dynamic and acoustic behavior of the system will confirm the suitability of this APU transducer to operate in food dehydration processes under a high power regime.

Fig. 3.37.- Evolution of the mechanical stress suffered by each component.

3.5- Numerical simulation of the ultrasonic field.

The last numerical simulation to carry out is the determination of the acoustic field generated by each ultrasonic system in the near and far field, under free field condition. This numerical simulation has been also done using the FEM software COMSOL Multiphysics®.

It is important to take into account that the ultrasonic systems analyzed in this chapter operate under a high power regime. This implies that the ultrasonic field generated is a high-intensity field and that the acoustic propagation will experience the nonlinear effects indicated in Annex A. Nevertheless, the numerical simulations of the 2D axisymmetric or 3D ultrasonic fields have been carried out under a linear regime because the state-of-the-art has not reached that far in terms of modelling of 2D and 3D nonlinear propagation in complex geometries.

The numerical simulation of the acoustic field generated by an ultrasonic system only includes the radiating plate and the surrounding gas medium. The rest of the elements of the transducer are not considered in these models in order to reduce its computational cost. In essence, the acoustic field is basically generated by the extensive radiator. The vibrator transmits a mechanical vibration to the radiator. This vibration is determined in terms of maximum displacements in the center of the

plate, for a certain electric supply. Hence, the operation of the vibrator can be simplified to a prescribed displacement applied to the basis of a rod connected to the center of the radiator.

On the other hand, the vibrator is a physical obstacle to the propagation of the ultrasonic fields. Nevertheless, it is located in the back face of the radiating plate, except for the APU transducer with flat rectangular radiator and with reflectors, where both faces are radiating. In this case, the narrow section of the mechanical amplifier has been lengthen by half wavelength in order to minimize this affection (see Chapter 2.4.2)

Therefore, the numerical analysis of the ultrasonic field has been done with a multiphysics analysis that comprises Solid Mechanics and Pressure Acoustics physics. The Electrostatics physic has been suppressed in these simulations.

The specific geometries, boundary conditions, meshing and results obtained for each simulation are presented in the following sections.

3.5.1- Meshing definition for the numerical analysis of the acoustic field

The simulation of acoustic fields is complicated in computational terms. APU transducers have extensive radiators and cover a wide area of the surrounding gas medium. Hence, the volume of gas medium to analyze is big, so the number of elements of the mesh that has to be defined.

The issue regarding the accuracy of the model as function of the size of the elements and the process capacity of the computer is important when carrying on 3D simulations. This fact is more critical when we need to work with high volumes like the acoustic field simulations.

The Shannon's sampling theorem leads the idea of using a fixed amount of elements per wavelength. In [131], an analysis of the error obtained for different type of elements and number of them per wavelength is presented. In the case of quadratic elements, and for a long duct filled with air, the conclusion obtained in [131] was that two elements per wavelength correspond to an error about 10 percent, so, it is recommendable to have, at least, two quadratic elements per wavelength.

Nevertheless, an initial convergence analysis was carried out. This study tried to confirm the previous conclusion, or to define the number of elements necessary for a convergent result. A 2D axisymmetric numerical analysis of the acoustic field generated by a radiator has been done for different meshes. The maximum size of the elements covering the propagation medium (air) was defined between $\lambda/2$ and $\lambda/20$, where λ represents the wavelength of the acoustic wave in air.

The propagation medium considered is air at a temperature of 20°C. The equation solved in the FEM model corresponds to the linear wave equation (Eq.3.4) in a lossless medium [132].

$$\nabla \cdot \left(-\frac{1}{\rho} \nabla p \right) - \frac{\omega^2 p}{\rho c^2} = 0 \quad \text{Eq.3.4}$$

The results of each simulation were defined as the average and maximum values of acoustic pressure and intensity obtained in a cylindrical chamber with sound hard boundaries. The results obtained after this convergence analysis are presented in Table 3.4, which presents the results

obtained for each parameter and the difference, in percentage, between these results and those obtained with the previous line, where the elements are one step bigger.

Table 3.4.- Convergence analysis of the meshing for the acoustic field simulation

Element size	Average acoustic pressure (Pa)		Maximum acoustic pressure (Pa)		Average acoustic intensity (W/m ²)		Maximum acoustic intensity (W/m ²)	
	Pa	%	Pa	%	(W/m ²)	%	(W/m ²)	%
$\lambda/4$	269		8082		23		3364	
$\lambda/6$	582	116	11811	46	158	598	14038	317
$\lambda/8$	215	63	5493	53	14	91	1175	92
$\lambda/10$	161	25	3602	34	8	521	865	26
$\lambda/12$	185	15	3826	6	13	84	1626.9	88
$\lambda/14$	188	2	3691	4	15	15	2068.6	27
$\lambda/16$	202	7	3822	4	19	26	2768	34
$\lambda/20$	201	0	3814	0	20	2	2853	3
$\lambda/25$	198	1	3759	1	19	2	2831	1
$\lambda/30$	197	1	3726	1	19	1	2801	1

The values of the four magnitudes considered are very erratic when the elements are bigger, obtaining big differences with the following simulations, with elements one step smaller. The results obtained with elements not bigger than $\lambda/16$ start converging, so, if it is possible, a maximum element size chosen for the numerical simulation of ultrasonic fields in air should be $\lambda/16$.

3.5.2- Acoustic field generated by an airborne power ultrasonic transducer with stepped-grooved circular plate

The numerical analysis of the mechanical behavior of the APU transducer with stepped-grooved circular radiator has been presented in Chapter 3.3. According to the results obtained, the transducer has an operational mode with a flexural mode with 7NC for the plate at a frequency of 25772 Hz. A harmonic electric supply of 100 V at the working frequency may reach displacements up to 3.2 μm in the plate, and a distribution of these along the radius as shown in Fig. 3.18.

The application of steps at the nodal circles of the plate, with a depth of half wavelength of the propagating acoustic wave through air may allow the generation of a coherent acoustic field, with constructive interferences in the near field for an energy concentration at the axis of the transducer. An ideal circular piston generates the perfect coherent field, whose pressure distribution in free field can be observed in Fig.2.10. The objective of the stepped circular radiator is to generate an acoustic field similar as the one generated by an ideal circular piston.

According to [5], which introduces the equation to define the acoustic field generated by a circular piston (Eq.2.3), an ideal circular piston with the same radius (177.9 mm) and vibrating at the same frequency (26957 Hz), generates an ultrasonic field with a near field up to 2.54 m from the radiator, and a far field away from that distance. The simulation of the acoustic field generated by the stepped-grooved circular radiator will try to identify the near and far field.

As with the numerical characterization of the behavior of the APU transducer with stepped-grooved circular radiator, the generated acoustic field has an axisymmetric behavior. Hence, a 2D axisymmetric model has been used for this determination. The stepped-grooved circular radiator, with the M10 bolt that act as a mechanical shaker, are radiating in a cylindrical chamber that is 2.5 m long.

As indicated before, a multiphysics analysis has been done, including a Solid mechanics and Pressure Acoustics physics. The boundaries of the acoustic chamber have been defined using PML's (Perfectly Matched Layers) with external Spherical Wave Radiation boundaries. According to COMSOL Multiphysics Reference Manual [133], a PML node applies a complex coordinate scaling to a layer of virtual domains surrounding the physical region of interest. When appropriately tuned, this layer absorbs all outgoing wave energy in frequency domain problems. This implies that the circular plate is radiating in free field.

A prescribed displacement of $10\ \mu\text{m}$ in Z-direction at the basis of the bolt is considered for this simulation. The location and direction of the prescribed displacement is presented in Fig. 3.38, where it can also be seen the axis directions corresponding to this 2D axisymmetric simulation:

Fig. 3.38.- Location and magnitude of the prescribed displacement applied to the bolt.

The meshing of the geometry is different for each element. The radiator and the bolt are meshed with free triangular elements with extremely fine size; the air mass has been meshed using free triangular elements whose maximum size is $\lambda/16$, according to the convergence analysis; and finally, the PML's are meshed by mapping the geometry. This mesh has a total of 2093248 elements with an average quality of 0.95. Details of the mesh and the histogram with its quality are shown in Fig. 3.39. It can be observed how the mesh is very refined with a high quality. Most of the elements of the mesh have a very good quality except a percentage of elements that have medium quality. These correspond to the PML, where the density of elements is lower and so is the quality in this area.

a) Mesh of the bolt and plate b) Mesh of the PML and plate c) Histogram with the quality of the elements
 Fig. 3.39.- Mesh of the geometry for the simulation of the acoustic field.

The first result is the determination of the limit between the near field and the far field. The acoustic distribution along the axis should be similar to the one for an ideal piston. This means that the near field should have a number of maximums and minimums in pressure and there should be an area with higher concentration of energy from which the acoustic pressure should decrease continuously. The simulated pressure distribution along the axis is shown in Fig. 3.40:

Fig. 3.40.- Axial acoustic pressure generated by the stepped circular radiator.

Of course, this distribution is not equal as the one of an acoustic field generated by a piston, but its shape is similar. There is an area with a succession of maximum and minimum amplitudes, whose separation is increased until an area with a higher energy concentration and a decrease of the pressure amplitude. In this case, this is not that evident, because it seems that the area with higher energy concentration is situated at about 0.5 m, although the energy decrease is not continuous.

The pressure distribution in a range up to 1.5 m is presented in a non-axisymmetric 2D view in Fig. 3.41, where it can be observed how the ultrasonic field is coherent, obtaining maxima energy concentration along the axis up to the edge between the near and the far field.

Fig. 3.41.- Pressure distribution generated by the APUT with stepped-grooved circular radiator.

The energy is concentrated along the axis of the radiator, with a series of areas with maximum and minimum pressure amplitude, and a continuous decrease.

The validation of this model will be carried out by an experimental campaign where the acoustic pressure distribution in the near and far field will be obtained. The results obtained after this experimental campaign are presented in Chapter 5.

3.5.3- Acoustic field generated by an airborne power ultrasonic transducer with flat rectangular plate

The numerical analysis of the mechanical behavior of the APU transducer with flat rectangular radiator has been presented in Chapter 3.4. According to the results obtained, the transducer has an operational mode with a flexural mode with 12NL for the plate at a frequency of 21049 Hz. A harmonic electric supply of 100 V at the working frequency may reach displacements up to $3.9 \mu\text{m}$ in the plate, with the displacement distribution along the plate as shown in Fig. 3.36.

As indicated in Chapter 2.4.2, the application of steps, coincident to nodal lines, in the surface of the plate, was proved not to be a good solution to obtain a coherent field. The use of a system of stepped reflectors may generate a coherent field and double the efficiency of the system by using both faces of the radiator.

Following sections will be focused on the numerical simulation of the ultrasonic field generated by the APU transducer without and with a system of reflectors.

3.5.3.1- Acoustic field generated by an APUT with flat rectangular plate without reflectors

As already mentioned, the computational resources required in a 3D simulation may be very big, depending on the size of the domain and the frequency of the wave. In this case, 2D and 3D simulations have been done for the ultrasonic field generated by the flat rectangular plate transducer, which is excited with a monochromatic continuous wave at the operational frequency, in order to induce the desired flexural mode with twelve nodal lines. The model of the transducer can be observed in Fig. 3.32, with the operational mode (12|0) presented in Fig. 3.34.

The first task should be the identification of the near and far field. In the case of a rectangular piston, the near field and the far field could be identified theoretically using the Rayleigh distance that, for plane radiators acting as a piston, can be determined using Eq.3.5 [134].

$$D = \frac{2\pi f a^2}{2c} \quad \text{Eq.3.5}$$

In Eq.3.5, a is half of the largest dimension of the radiator. The separation between the near field and the far field is located at a distance of $1/\pi$ of the Rayleigh distance. This theoretical equation is suitable for a rectangular piston. According to Eq.3.5, the Rayleigh distance of a rectangular piston with these dimensions is 15.7 m, meaning that the separation between the near and far field is located at around 5 m from the source. Nevertheless, the transducer is not acting as a piston because it vibrates in a flexural mode, and the previous calculation should be considered as a mere reference.

In order to set an approximate frontier between a hypothetic near field and far field, a 2D numerical determination has been done, obtaining the ultrasonic field in the plane XY to delimit the size of the 3D simulation to an area near the transducer, with a pressure distribution similar to the one of an ideal piston. The simulations are done considering free field propagation, by defining PML's in the boundaries of the fluid domains. The 2D simulation allows a larger distance with higher resolution because the number of elements is much smaller than a 3D simulation, as well as the required computational resources.

In the same way, two 2D simulations have been done, an initial simulation reaching up to 10 m from the rectangular plate, to delimit the limit between the near and far field, and a second simulation focused in the near field, with a finer mesh.

According to the analysis presented in Chapter 3.5.1, the maximum element size recommended in acoustic simulations is $\lambda/16$, that in this case corresponds to a maximum size of 1 mm. Nevertheless, the computational requirements for a simulation up to 10 m make it impractical to have such fine mesh. Hence, the mesh considered in the initial approach is composed by free triangular elements with a maximum size of 2.6 mm in the propagating medium, which provides six elements per wavelength. The plate and rod are defined with extremely fine elements and the PMLs are meshed by mapping the geometry. The final mesh has 2690659 2D elements with an average quality of 0.9521. The model, details of the mesh and histogram are presented in Fig. 3.42.

A prescribed displacement of 10 μm at the basis of the rod is applied for this simulation. The first result is the determination of the limit between the near field and the far field, to delimit the area of the acoustic field simulation, with a higher element resolution. The flat rectangular radiator is not capable of generating a coherent ultrasonic field because the steps (delays) are not applied in its surface, so different areas of the surface vibrate in counter-phase and the interferences obtained are not constructive. Nevertheless, the pressure distribution at the axis of the radiator may show a combination of the behavior of the two dimensions, with number of maximums and minimums in the near field and a continuous decrease of the acoustic pressure (Fig. 3.43).

According to this, it is not easy to define the limit between near and far field, but it can be situated at about 1 m from the radiator. This result differs from the theoretical calculation done with Eq.3.5, which stated this limit around 5 m.

The simulation with $\lambda/16$ big elements will comprise 3 m from the radiator. The mesh of the propagating medium is composed by free triangular elements with a maximum size of 1 mm. The other elements of the system are meshed in the same way as indicated in Fig. 3.42. The final model has 5718875 elements, with an average quality of 0.9541. This new model and the histogram are presented in Fig. 3.44, and the acoustic field generated by the transducer can be observed in Fig. 3.45.

The pressure distribution in the 2D plane clearly shows the limit between the near field and the far field, at a distance of 1 m, where the last maximum appears. The pressure distribution in the near field is not coherent, but parallel lines with minimum energy appear. These lines correspond to the projection in the medium of the nodal lines of the rectangular plate. The absence of coherent interferences implies this distribution.

Another simulation, corresponding to a 3D model, has been done in the near field, to obtain the pressure distribution in planes parallel to the radiator and in the plane XZ.

As mentioned before, 3D simulations require much higher computational resources, making it inviable to cover a wide volume with a fine mesh. To overcome this issue, the simulated model corresponds to a quarter, applying symmetry where needed, and with a coarser mesh.

In this case, the chamber analyzed is 1.3 m long, and the mesh applied has a maximum size of 7 mm in the medium, which implies more than two quadratic elements each wavelength. According to this, the mesh has 2657055 3D elements, with an average quality of 0.6658. This new model and the histogram are presented in Fig. 3.46.

Fig. 3.46.- Geometry and mesh for 3D model.

This 3D simulation allows the possibility to obtain 2D slices parallel to the surface of the radiator, in order to view the acoustic evolution in the near field (Fig. 3.47).

Fig. 3.47.- Slices in the YZ plane, parallel to the flat radiator, at different distances.

It can be observed in Fig. 3.47 pressure nodes affected by the nodal lines of the radiator, and how the pressure map becomes more homogeneous when the distance with the radiator is increased. Two areas with maximum pressure values appear in Fig. 3.47.f, corresponding to the YZ slice at a distance of 968 mm from the transducer. The energy focuses on these areas, originating two directional lobes. These lobes can be observed in Fig. 3.48, and in the directional patterns presented in Chapter 5.2.5.

Fig. 3.48.- Acoustic pressure distribution in the plane XZ up to 1.1 m.

It has been presented the ultrasonic field generated by the APU transducer with flat rectangular radiator. This simulated field does not look like a coherent field because the interference pattern is not constructive. A system with stepped reflectors can be added to produce the required delays that generate constructive interferences and, hence, a coherent ultrasonic field.

3.5.3.2- Acoustic field generated by an APUT with flat rectangular plate with reflectors

The numerical simulation of the acoustic field generated by the ultrasonic system with reflectors (SWR) has been done in a 3D model. The computational resources required in this simulation are higher because it is needed to simulate two acoustic fields, the field obtained in the space between the transducer and the reflectors, and the field that the system generates into the free field. In order to reduce these computational resources, a two-step simulation has been done, obtaining the amplitude pressure map at the output of the SWR in the first one, and using this result as an input in the second step that is the free field simulation. The model of the ultrasonic SWR and the axis orientation of this simulation are shown in Fig. 3.49.

Fig. 3.49.- Model of the ultrasonic system with reflectors (SWR).

As mentioned before, the first simulation tries to determine the nature of the ultrasonic field generated by a virtual radiator that would be the output of the ultrasonic system, which corresponds to the YZ plane in Fig. 3.49.

In order to reduce the computational resources required to do this simulation, and taking into account that the model is symmetric, only a quarter of the system has been analyzed, applying symmetric boundary conditions and rebuilding the whole model for presentation purposes. This quarter geometry is shown in Fig. 3.50, where the elements of the system are highlighted. The radiating plate is highlighted in green; the symmetry boundary of the air mass is highlighted in red, and the PML is highlighted in blue. It is not necessary to define the material of the reflectors (colored in grey) because they act as mere sound hard boundaries. The two images correspond with two different views of the system, where the steps applied in the reflectors are easily visible, as well as barriers situated inside this volume, which are in the steps.

Fig. 3.50.- Quarter of the model of the ultrasonic SWR.

The first simulation consists of the determination of the ultrasonic field at the output of the SWR, which is the amplitude pressure field of the virtual radiator. The area where the acoustic distribution is simulated is the limit between the system and the PML, as it can be observed in Fig. 3.50. The plate and volume under analysis have been meshed using free tetrahedral elements with a maximum size of 4.1 mm, that is a quarter wavelength, in the propagating media, and a maximum size of 8 mm for the plate. The final mesh has 5872424 elements, with an average quality of 0.66. The mesh and histogram can be appreciated in Fig. 3.51.

a) Mesh of the ultrasonic SWR b) Histogram with the quality of the elements
Fig. 3.51.- Mesh of the ultrasonic SWR.

The simulation of the acoustic field has been done for an operational mode of the rectangular plate at 21 kHz and a prescribed displacement of 10 μm . The acoustic distribution inside the reflectors system and at the output is presented in Fig. 3.52.

Fig. 3.52.- Acoustic distribution inside the reflectors system.

The pressure amplitude distribution presented in Fig. 3.52.b is introduced as an initial value for the free field simulation, in order to determine the acoustic field generated by the whole system. This simulation also corresponds to a 3D simulation that involves only the pressure acoustics physics.

The volume under study is a 1 m long prism, where PML's have been defined to simulate free field conditions. The input corresponds with the pressure distribution presented in Fig. 3.52.b.

The volume has been meshed using periodic elements with a maximum size of $\lambda/4$ for each 3D quadratic element. This geometry, with a hexahedral shape allows the use of periodic elements in the meshing. The number of elements is 2945241, with an average quality of 0.9932. This model, meshing and histogram are presented in Fig. 3.53.

a) 3D model of volume of interest

This acoustic field, determined numerically under free field conditions, is presented in Fig. 3.54, where the XY plane and the XZ plane are shown:

On the other side, YZ planes, parallel to the virtual radiator, are also presented in Fig. 3.55, to view the acoustic evolution near the radiator:

Fig. 3.55.- Slices in the YZ plane, parallel to the flat radiator, at different distances.

Comparing the pressure distribution obtained with the flat rectangular plate and the pressure distribution obtained with the ultrasonic system, it can be perceived that the latter doubles the area of interest, and that there are higher pressure amplitudes in the free field. This event is produced by constructive interferences that happen after putting in phase the acoustic waves with the reflectors. The experimental analysis will confirm the improvements obtained with the SWR, and will validate the numerical model used in these simulations.

3.6- Conclusion.

The initial step in the development of APU transducers is the theoretical and numerical design of its components. This Chapter 3 is focused in the numerical simulation of the two transducers considered, using the FEM software COMSOL Multiphysics®. The theoretical initial analysis has been proved to be a good approach to the design of these transducers but it is not very accurate due to the special geometries of each element, so the use of FEM is necessary to avoid trial and error designing method.

The design of the APU transducer with a stepped-grooved circular radiator has been completed, obtaining a transducer that vibrates in an operational mode with 7NC at about 25.8 kHz.

On the other hand, the design of the APU transducer with a flat rectangular plate obtained a system that vibrates in the desired mode with 12NL around 21 kHz. The development of this system included an extended theoretical analysis of vibration of rectangular plates, to adapt the Caldersmith equation to thicker plates or plates with higher vibration modes.

Finally, the acoustic effect of the addition of a stepped reflector system has also been analyzed, obtaining a more homogeneous ultrasonic field with higher-pressure amplitudes than the system without reflectors.

The work presented in this chapter is the first stage of the development of APU transducers for food dehydration purposes.

The design of the stepped-grooved circular plate transducer has been subject of the following conference papers and presentations:

- **Conference paper.** 2016. R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "Description of an ultrasonic technology for food dehydration process intensification," Proceedings of Meetings on Acoustics, vol. 28, p. 045003.
- **Congress presentation.** 2016. R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "New ultrasonic technologies for food dehydration process intensification," in 22nd International Congress on Acoustics (ICA), Buenos Aires (Argentina).
- **Congress presentation.** 2018. R. R. Andrés, V. M. Acosta, A. Pinto, and E. Riera, "Airborne power ultrasonic systems for food dehydration processes intensification," presented at the 25th International Congress on Sound and Vibration, Hiroshima (Japan).

The design of the flat rectangular plate transducer has been subject of the following publications:

- **Journal paper.** 2018. R. R. Andrés, V. M. Acosta, M. Lucas, and E. Riera, "Modal analysis and nonlinear characterization of an airborne power ultrasonic transducer with rectangular plate radiator," Ultrasonics, vol. 82, pp. 345-356, 2018/01/01.
- **Journal paper.** 2020. R. R. Andrés, E. Riera, " Application of the Caldersmith expression for the study of rectangular radiators for power ultrasonic transducers," International Journal of Acoustics and Vibrations (in press).
- **Conference paper.** 2016. E. Riera, V. M. Acosta, J. Bon, M. Aleixandre, A. Blanco, R. R. Andrés, et al., "Airborne Power Ultrasonic Technologies for Intensification of Food and Environmental Processes," Physics Procedia, vol. 87, pp. 54-60, 2016/01/01.
- **Congress presentation.** 2017. R. R. Andrés and E. Riera, "Considerations regarding the design of a power ultrasonic transducer with flat rectangular plate," presented at the COMSOL Conference, Rotterdam, 2017.

The next contributions have been obtained from the numerical simulation of the acoustic field for the two systems:

- **Journal paper.** 2019. R. R. Andrés, A. Pinto, et al. "Acoustic field generated by an innovative airborne power ultrasonic system with reflectors for coherent radiation," Ultrasonics, p. 105963, 2019/07/15.
- **Congress presentation.** 2017. R. R. Andrés, V. M. Acosta, and E. Riera, "Ultrasonic field generated by different airborne power ultrasonic transducers with extensive radiators," in Tecnicústica 2017: 48º Congreso Español de Acústica. A Coruña 3-6 Octubre 2017.
- **Congress presentation.** 2017. R. R. Andrés, E. Riera, et al. "Coherent sound field generated by an airborne power ultrasonic transducer with rectangular plate radiator for food dehydration purposes," in UIA Symposium, Dresde (Germany)

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4.- EXPERIMENTAL CHARACTERIZATION OF AIRBORNE POWER ULTRASONIC TRANSDUCERS

The use of power ultrasonic systems has been proved to be useful in enhancing the process of a wide range of industrial applications. Nevertheless, the transducer is usually subjected to a very demanding operational mode, to produce the desired effects with an acceptable efficiency of the system.

Ultrasonic systems working under a high-power regime are likely to experience some nonlinear effects, with different origins. A proper design of the transducer, with a good tune of the different components, and paying special attention to minimize the nonlinear effects like modal interaction or autparametric behavior, is crucial for a good performance of the system.

The traditional “trial and error” methodology for the design of mechanical systems allowed a slow and expensive approaching to a good design, because any kind of modification in the initial design had to be machined again, taking time and money.

The possibility of FEM simulations reduces the time and materials used in any mechanical design, implying a much cheaper process. This numerical design allows the necessary number of modifications of the initial layout to predict the desired performance, if all the parameters involved in the numerical simulation have been chosen correctly.

Nevertheless, when a final design, in which the predicted operational behavior is acceptable, has been reached, a prototype has to be built and its performance has to be proved under several circumstances. A set of experimental studies has to be carried out. These analyses involve electrical, mechanical and acoustical measurements, to cover the three aspects of the operation of the transducer. The experimental characterization of the behavior of an airborne power ultrasonic transducer includes the following experiments:

- Low power characterization with an impedance analyzer. The impedance analyzer supplies low power to the transducer (up to 1 V_{rms}) [135], enough to identify the operational frequency and other near modes, and quantifies the electrical response of the system
- Stability tests. The transducer is working continuously at its operational mode, with a periodically increasing power supply. The aim of this test is to identify failures or other effects from fatigue.
- Dynamic characterization. This consists on a series of experiments under different operative conditions to check the existence of mechanical nonlinear effects.
- Modal analysis. This is a specific experiment that tries to identify the modal behavior of the transducer, to preview the possibility of modal nonlinear effects when the transducer operates under high power regime.
- Acoustic behavior. The final set of experiments is necessary to characterize the acoustic field generated by the transducer, in terms of pressure distribution in the near and far field, and determination of the directivity pattern.

4.1- Low power characterization.

This first experimental analysis is a low power characterization, using an impedance analyzer Hewlett-Packard 4194A. The impedance analyzer allows a full electric characterization of the ultrasonic system. Among the variables characterized with the impedance analyzer we can find the resonance frequency, conductance at resonance, impedance, bandwidth and the quality factor. The impedance analyzer used for these experiments are presented in Fig.4.1:

Fig.4.1.- Impedance analyzer HP 4194A.

The experiments carried out with this impedance analyzer consist on a series of frequency sweeps covering different ranges, taking into account that each measurement is done in a maximum of 401 points. This means that the wider the measuring range, the lower the resolution obtained.

The objective of this experiment is the electrical response of the ultrasonic system at the operational frequency and the search of other undesired modes near the working one. So, the initial sweeps are carried out to identify the eigenfrequencies of the system, and then, to narrow the measurement range to an interesting area.

This interesting area may correspond to the operational mode and other near modes. The magnitudes quantified with this test are the conductance (G), which is defined as the ability of a system to conduct electricity, measured by the ratio of the current flowing through the system to the potential difference across it. It is quantified in Siemens (S).

The reciprocal of the electric conductance is the electric resistance (R), which corresponds to the real part of the impedance (Z), which is a measure of the opposition to the flow of an alternating current. The impedance is expressed in ohms (Ω).

The bandwidth (BW) of the transducer at the working mode is calculated with the Bode plot of the evolution of the conductance (G) around resonance. It is the range (in Hertz's) between the two

points where the maximum conductance, obtained at the resonance frequency, decays to the half of its value. The determination of the bandwidth can be easily observed in Fig.4.2.

Fig.4.2.- Bode plot with the determination of the bandwidth of a transducer.

The quality factor (Q) is associated to the efficiency of the system, and can be determined applying Eq. B. 10, which relates the central frequency and the bandwidth at resonance. The higher the quality factor, the more efficient the system is, but also, the more unstable.

Finally, the low power characterization with the impedance analyzer provides information about the value of the parallel capacity (C_0), necessary to determine the value of the compensation inductance (L_0) that will be necessary to be applied physically in the impedance matching unit or electronically when the transducer works under operational conditions (see Eq. B. 16).

Therefore, this initial approach to the behavior of the system provides good information about the electrical behavior of the transducer, and the existence of undesired modes near the working frequency.

4.2- Stability tests.

One of the main factors limiting the maximum acoustic energy that an airborne power ultrasonic transducer can transfer into a gas medium is the power capacity of the transducer and the fatigue limit below which tuned components must operate. The aim of stability tests is to determine the behavior of ultrasonic systems when operating at high power for a long duration, in terms of both fatigue and modal interactions. When an airborne power ultrasonic transducer operates continuously, eventually the constitutive parts can experience effects due to fatigue. In fact, fatigue is a term that applies to changes in properties of materials subjected to cyclic mechanical stresses or strains and can lead to component fracture and failure. Experimental tests [136] have shown that the maximum stress that can be applied without danger of ultrasonic fatigue is approximately

30 MPa for aluminum and 200 MPa for titanium alloy, that are materials commonly used in the manufacturing of power ultrasonic transducers.

For repeated operation, it has been stated that, although aluminum continues degrading with use, the fatigue limit is $5 \cdot 10^8$ cycles [111], meaning that if no undesired behavior appears before this limit, no other effect is expected due to fatigue. On the other hand, ferrous metals like low carbon steel or titanium don't have this fatigue limit but the endurance limit that is the stress for which failure does not occur, even for an indefinitely number of loading cycles. The relationship between suffered stress and number of cycles for ferrous (like titanium) and nonferrous (like aluminum) materials is presented in Fig.4.3 [111].

Fig.4.3.- Typical σ -n curves.

For our stability analysis, we will consider the most restrictive case to determine the fatigue limit for our materials. In this case, we will use the fatigue limit of $5 \cdot 10^8$ cycles as the most adequate.

For all power ultrasonic transducers, there is a displacement in the tuned resonance frequency during continuous operation due to heating of the ceramics and other components. It is then possible for energy to be shared with other modes if the modal density of the transducer is high. This then reduces in the efficiency of the system and increases the risk of fatigue failure.

The ultrasonic signal generation system used to carry out the stability tests consists of a dynamic resonance frequency control unit (ultrasonic controller), to give adjustable continuous power output at the resonance frequency of the transducer by keeping the voltage (V) and current (I) signals in phase, and tracking it when this frequency shifts during operation [95, 137]. The controller operates as a finely tuned electronic signal generator that sends the excitation signal to a broad-band power amplifier and then to the transducer through an impedance matching unit to allow maximum energy transfer between the electronics and the transducer.

The electrical response of the transducer can be measured at the output of impedance matching unit by sampling the voltage and current signals that are sent back to the controller. This displays information about voltage, current, power, impedance and phase. Additionally, an oscilloscope displays the frequency spectrum of this response, which can be used to check any

possible modal interaction. The block diagram of the power electronic system is shown in Fig.4.4, and the different elements necessary for this analysis are presented in Fig.4.5.

Fig.4.4.- Block diagram of the power electronic system for stability tests.

Fig.4.5.- Elements of the stability tests measurement chain.

The ultrasonic controller has been manufactured by Department of Electronic Engineering of the Power Ultrasonics Group. It uses the voltage and current samples taken from the output of the impedance matching unit to keep the ultrasonic system working at its operational mode. The controller also gives information about several electrical variables (excitation frequency, voltage, current, supplied electric power, phase and impedance).

The next element of the measurement chain is a power amplifier, QSC RMX 4050HD. This is a two channels power amplifier, but it can operate in a bridged mode to supply higher output power. This commercial amplifier has been designed for audio purposes, so, it is suitable for the audible frequency range (20 Hz – 20 kHz). Hence, the cut-off frequency happens at 20 kHz, below the usual working frequency of power ultrasonic systems (between 20 kHz and 40 kHz). Nevertheless, the ultrasonic systems designed and presented in this work operates at frequencies between 20 kHz and 26 kHz, near this cut-off, so, the power amplification obtained with this amplifier seems to be good enough for this purpose.

The maximum output power supplied by the amplifier, working in a bridge mode, at a frequency of 20 kHz and for an electric resistance of $8\ \Omega$ is 2600 Watts, much higher than the electric power that our ultrasonic transducers can handle. Anyway, a following stage, that is the impedance matching unit, provides an impedance adaptation between the output of the power amplifier and the ultrasonic system.

The electric impedance of airborne power ultrasonic transducers depends, mainly, on the shape of the radiator, more specifically on the area of the radiator. A sonotrode or vibrator without extensive radiator has much smaller impedance than a transducer with a circular or rectangular radiator, whose impedance can reach about $400\ \Omega$ or $500\ \Omega$ in resonance. So, the impedance matching unit is a system, developed by the Department of Electronic Engineering of the Power Ultrasonics Group, whose mission is to modify the impedance at the input of the transducer to make it similar as the impedance of the transducer radiating on air.

The samples that travel back to the ultrasonic controller are taken from the input of the transducer, and give information about the electrical behavior of the whole system. These signals can be analyzed in real time by sending them to the oscilloscope (Tektronix DPO 7054) where they can be observed both in time and frequency domains.

The experimental methodology of the stability tests consists on the observation of the electric variables when the transducer operates at its working frequency. The operation of the transducer starts with a low power supply to observe if the behavior is adequate. The electric variables are logged periodically, and the signal observed in the oscilloscope is checked.

If the electric behavior is correct after a long operation of the transducer, the power supply is increased in variable steps depending on the properties of the transducer, letting the system work continuously during long periods and checking all the variables periodically for each step.

For a transducer with a working mode at 20 kHz, the previously mentioned fatigue limit of $5 \cdot 10^8$ cycles is reached at about 7 hours of continuous working. Nevertheless, when working at high power, we prefer to be on the safe side, considering that the transducer has low risk of failures due to fatigue when it has been tested during at least 24 hours without the appearance of any instability.

The distortion of the time signal is a sign of instability or saturation of the system. The shape of the voltage and current signals can be observed in the screen of the oscilloscope. The absence of distortion and a good performance of the system are reflected as a sine wave in the time domain, and a delta in the frequency domain. A distorted signal shows a modified wave in the time domain,

which is the sum of the main frequency and the harmonics that have been excited now. An example of a clean and a distorted signal (sawtooth wave) with a fundamental of 21 kHz is presented in Fig.4.6, both in the time and frequency domains.

Fig.4.6.- Clean and distorted signals.

The transducers subjected to stability tests operate continuously during several days with an increasing supplied power. Two main results can be obtained after this analysis: the possibilities that the transducer suffers fatigue, and an estimation of the power capacity of the system.

The power capacity of an ultrasonic system is related to the maximum power that the system can work with, before suffering saturation and other failures. In the stability tests, a relationship between the excitation voltage and the obtained electric power can be determined, as presented in Fig.4.7, where two areas can be appreciated: for voltage under 6 V, the relationship between the two parameters is exponential, while over 6 V the system reaches a saturation and, the output electric power does not increase its value.

4.3- Nonlinear dynamics characterization.

The following step consists on a detailed experimental campaign that tries to identify several potential nonlinear effects like those presented previously.

This set of experiments comprises low and high power regimes and measurements both in the electrical field, by taking samples of the electrical response of the transducer to different stimulus,

and in the mechanical field, by measuring displacement amplitude in some places of the extensive radiator with a 1D vibrometer laser. The nonlinear dynamics characterization of APU transducers can be done with two different systems developed with Labview[®], and described in Annex G.

Fig.4.7.- Relationship between excitation voltage and power.

4.3.2- Determination of the nonlinear behavior of an airborne power ultrasonic transducer

After carrying out the low power experiments in the impedance analyzer, which give the spectral information about the location of the operational mode and the existence of other modes; and the stability tests, which results in a good knowledge about the risks due to fatigue and about the power capacity of the system, the following set of experiments are focused on dynamic nonlinear effects related to hysteresis, frequency drops, or other modal nonlinearities.

The methodology for this determination is based on two different kinds of experiments: a first kind where the transducer operates continuously at resonance; and other kind of experiments based on frequency sweeps in more or less wide ranges around resonance and with different excitation parameters.

4.3.2.1- Nonlinear experiments under continuous operation regime

This Labview[®]-based system allows a resonance tracking as explained before. With this system it is also possible to perform stability tests. Actually, experiments under continuous operation regime have a similar methodology. The operation parameters can be established: for example, a continuous operation with an increasing supplied voltage, in steps of 10 V each 60 seconds, and data logging each 10 seconds; or continuous operation at resonance with a supplied voltage of 100 V, with a data logging each 60 seconds, to evaluate the temperature evolution during operation.

The higher capacity of analysis of the response of the transducer makes it possible to determine the evolution of several magnitudes (temperature, frequency, power, current, vibration velocity or displacement, etc....) with respect to other magnitudes like time or excitation voltage; and to establish the analytical function corresponding to that behavior.

4.3.2.2- Frequency sweeps

The main nonlinear dynamic characterizations are based on frequency sweeps around resonance. This means that the system generates an electric signal at a continuously varying frequency upwards and/or downwards to measure the response of the transducer depending on the frequency variation. Nonlinear effects like frequency shifts, hysteresis or drops can be detected with this technique.

There are experiments that perform 1D frequency sweeps which means that only frequency is varying during the sweep, in both directions, upward and downward. For example, a Langevin-type transducer, with two separate stacks with two piezoelectric ceramics each, can be tested with a 1D sweep. This transducer can be observed in Fig.4.8. The thickness mode of the transducer appears at 21362 Hz, and it has a bandwidth of 55 Hz. The sweep has been done between 21000 Hz and 21600 Hz, in steps of 0.2 Hz each 100 ms and a supplied voltage of 1 V. This means that the generated electric signal starts in 21000 Hz, with 1 V, and increases its frequency by 2 Hz each 100 ms until reaching 21600 Hz. At this point, the generated signal will decrease its frequency in 2 Hz each 100 ms, until reaching 21000 Hz. The result obtained after this experiment is presented in Fig.4.9.

Fig.4.8.- Langevin transducer with two separated ceramic stacks.

It can be observed how the resonance is slightly displaced in the downward sweep, to a lower frequency. This is a frequency shift. This experiment can be completed with a 2D frequency sweep, which includes variations in the excitation frequency and voltage, between 1 V and 10 V, as shown in Fig.4.10, where a number of nonlinear effects can be observed. The first effect is a softening behavior (Fig.2.19), considering that the resonance frequency moves to a lower value when increasing the supplied voltage. On the other hand, for electric supplies over 3.25 V, and upwards direction, part of the energy “disappears”, leaving a hole. This seems to be a parametric excitation (Fig.2.24). Downward sweeps also show nonlinear effects like hysteresis and jump phenomena (Fig.2.20). As a conclusion, it is proved that this transducer shows a number of different nonlinear effects when applying power.

Fig.4.9.- Example of a 1D frequency sweep around resonance.

Finally, among the nonlinear effects that can lead to a malfunctioning of the system is an excessive temperature in weak areas. A continuous operation of the transducer can originate that the temperature in the ceramics, bolts or joints between each components increase uncontrolled.

Some results of the nonlinear dynamic characterization may be affected by temperature raises when operates continuously. To minimize the effect of temperature in the system, a burst excitation can be used. This type of excitation inserts periods with no supplied voltage with periods with an electric supply at the desired frequency and amplitude. The acquisition system (DAQ unit and Labview[®] application) only considers the response of the transducer when the generation system supplies electric power. A sync signal (Fig. G. 2) permits a good synchrony between the elements. An example of a burst excitation is presented in Fig.4.11.

Fig.4.10.- Example of a 2D frequency sweep around resonance.

The configuration of the burst can be also done with the application built in Labview®. The response of the transducer supplied with a burst signal minimizes the effects of temperature, showing a different behavior, depending on the nature of the system.

Fig.4.11.- Example of a burst excitation signal.

4.3.2.3- Spectral distribution of the energy

One of the main concerns related to the operation of APU transducers is to know how much energy will be transferred to higher harmonics or to other frequencies with an arithmetic relationship with the resonance frequency (autoparametric excitation).

So, another experiment to carry out when applying high power to the transducer is the determination of the spectral distribution of the mechanical energy obtained as a result of the operation of the ultrasonic system. This mechanical energy corresponds to the vibration velocity measured with the 1D laser vibrometer pointing to an area of the radiator with maximum displacements.

To evaluate the spectrum of the mechanical vibration of the APU transducer, a Fast Fourier Transform (FFT) can be carried out. This process consists on doing a frequency sweep upwards and downwards with a high excitation level. This first sweep will be used to select points of the curve where the FFT will be done. These points are associated to excitation frequencies and the response of the system in terms of vibration velocity.

In a second frequency sweeps, the signal measured by the laser vibrometer at the chosen points are transformed using the FFT, in order to determine the spectral distribution in the desired frequency range, and to observe the existence of autoparametric excitation and the appearance of harmonics.

4.4- Experimental modal analysis.

Previous experiments give information about the modal spectrum of an ultrasonic system, and about the possibility of the appearance of modal interactions when supply high power. Nevertheless, the experimental modal analysis is one of the most popular techniques for measuring the vibration behavior of vibrating structures.

As explained in [138], the experimental modal analysis (EMA) relies on the application of a modal parameter estimation method (curve-fitting) to a set of measurements carried out on the

structure under investigation. It is based on a set of measurements using a 3D laser vibrometer (Polytec CLV 3D), capable of measuring the vibration velocity in three orthogonal directions.

The transducer is excited with low power, using a sine sweep in a broadband frequency range and its mechanical response is measured at several locations with the 3D laser vibrometer, obtaining signals in the time domain. The results are transformed into the frequency domain and processed using the ME'Scope modal analysis software, in order to obtain a theoretical expression to the measured frequency response function (FRF) of the transducer, which is a relationship between the response of the system and the input reference. The results are the natural frequencies and mode shapes of the ultrasonic system. The block diagram for these experiments is shown in Fig.4.12.

According to [138], there are four basic assumptions to consider when carrying out modal analysis experiments:

- Linearity. We assume that the studied structure behaves linearly with the applied excitation. In practice, this is not real, so we aim to have a good approximation of the real behavior of the system.
- Time independency. We consider that the response of the transducer is not time dependent, so, the modal parameters are constant. Power ultrasonic devices are subjected to temperature increases, which may change its modal behavior. This is the reason why the modal analysis experiments are taken with a low power, to avoid temperature rises and have a constant modal behavior.
- Reciprocity.
- Observability.

Fig.4.12.- Block diagram for the experimental modal determination.

The first step is the definition of the geometry of the element that will be analyzed, as well as a grid of measurement points on the surfaces of the ultrasonic system, sufficiently fine to identify accurately all the mode shapes in the measured frequency range. The points of the grid define a

wire-mesh model of the device that is used in the modal analysis software (ME'Scope) to represent the vibrational shapes at each modal frequency. As an example, the geometric definition of the Langevin transducer with two stacks with two piezoelectric ceramics separated from the center of the transducer, presented in Fig.4.8, has been done. In this case, the real transducer is cylindrical, but for this example only four points have been considered in its perimeter because they are enough to identify flexural and torsional modes. For this reason, the sandwich looks like a square prisms instead of a cylinder.

Fig.4.13.- Geometric definition of a Langevin transducer for a modal analysis.

In this model, a total of 52 grid points covers the whole area of the transducer, and are the areas where the mechanical displacements are obtained. A broadband electric supply, with low power, is applied to the transducer, and the 3D laser vibrometer measures the mechanical response as displacements in the three orthogonal directions, in all points of the defined grid.

Fig.4.14.- Modal spectrum obtained for the Langevin transducer, between 14 and 33 kHz.

A broadband frequency response function is obtained at each measurement point. The analysis software ME'Scope composes a matrix with the FRF's obtained at each point. This matrix represents the dynamics of the whole system, as the ratio of the output response to the input excitation force. The FRF matrix multiplies the inputs to obtain the outputs, in the frequency domain. The modal spectrum of the transducer, obtained from the FRF matrix, is presented in Fig.4.14.

The way to estimate the modal characteristics of the measured transducer is perfectly explained in [139]. The curve fitting technique is used to extract modal parameters like frequency, damping and mode shapes. This technique basically breaks the measured FRF into many single DOF systems, as shown in Fig.4.15 [139].

Fig.4.15.- Breakdown of the frequency response function.

Applying curve fitting techniques to the spectrum presented in Fig.4.14, we can find the modal parameters like the natural frequencies and mode shapes. The results obtained from the modal analysis of the Langevin transducer shown in Fig.4.13 are presented in Fig.4.16.

Experimental modal analysis tests provide information about the modal behavior of an ultrasonic system, location of the natural frequencies and possibilities of a modal interaction when applying power.

4.5- Acoustic characterization.

Once the electro-mechanical behavior of the transducer has been studied, as well as its performance under working conditions of high power and long term operation, the following determination is the acoustic effects generated by the operation of acoustic systems in the surroundings.

It has been proved that the application of power ultrasounds in food dehydration processes have shown a better performance in terms of efficiency, energy reduction and quality of the final product [140, 141], allowing also a reduction in the convective drying kinetics, and at lower temperatures than conventional air dryers [44]. The ultrasonic energy, generated by the APUT, is capable of modifying the moisture content within the food samples, depending on their properties like porosity, hardness and flow resistance. When high-intensity waves couple with the samples,

some mechanical expansions and contractions happen in structure as an influence of the ultrasonic energy, originating the so call “sponge effect” [142]. As a consequence of this effect, the moisture separates from the walls of the solid structure of the samples, where it is attached, and is removed through the capillary out of the food sample.

Fig.4.16.- Natural frequencies and mode shape of the Langevin transducer.

The ultrasonic field generated by an ultrasonic system for food dehydration has to fulfill two main requirements: this field needs high values of pressure amplitude to be able to provoke the “sponge effect”, and the radiation has to be coherent to have constructive interference and cover wider areas for a higher efficiency of the system.

The desired acoustic field in this work is coherent, similar as the field generated by a piston. Nevertheless, other food dehydration applications may use different ultrasonic fields, like the system presented by [143], with a convective drying assisted by microwaves and ultrasound, where the ultrasonic field generated by this system is focalized on an specific area of rotating pan where the food samples are situated.

The study of the acoustic field comprises two different experiments, which are the experimental determination of the acoustic field generated by the ultrasonic system in the near and far field, and the directivity pattern of that system.

4.5.1- System for the experimental determination of the ultrasonic field

The experimental characterization of the acoustic pressure amplitude field generated by the two analyzed APUTs (with a stepped-grooved circular plate and with flat rectangular plate without and with a reflector system) has been carried out in a semianechoic chamber, where a PC-controlled

3D measuring system was used. The X, Y, Z coordinates related to the microphone position are governed by means of numerical control equipment (Labview® code), and they are sent to an analogue treatment stage.

2D raster scans, which measure the SPL, have been done with a 1/8" pressure microphone (GRAS 40DP), capable of measuring low frequency ultrasound. The measuring process consists of an initial 1D scan along the axis normal to the surface of the transducer, with the microphone moving in a continuous way along the axis, in order to identify the limit between the near and far field, and then, determine the location of maximum pressure amplitude points in the near field. The acoustic pressure amplitudes were determined from the voltage measurements, taken with a spatial resolution of 1 mm associated to the limitations of the measuring setup.

Then, 2D raster scans have been carried out in planes parallel to the radiating surface of the transducer where the maximums in the near field are located. In these scans, sweeps covers the desired plane, with continuous displacements along the y-axis, and steps of 1 mm in the z-axis. Pressure measurements in planes perpendicular to the transducer emitter surface have been obtained with 2D Raster scans with a continuous movement along the y axis and 1 mm steps in the x axis.

The experimental setup is composed by an ultrasonic controller, whose task is to drive the transducer into the desired operational mode, and track this mode even if the working frequency moves. The signal travels to an impedance matching unit through the amplifier and then to the transducer, which vibrates at the required frequency and generates the ultrasonic field that is measured as explained before.

Fig.4.17.- Block diagram for the ultrasonic field experimental setup.

The electrical output of the microphone, registered at each point, is stored on a PC. The output voltage level from the microphone is then converted to the equivalent acoustic pressure (Pa), using the sensitivity of the microphone (1 mV/Pa). The block diagram of the measurement setup is shown in Fig.4.17.

As mentioned before, the experimental determination of the ultrasonic pressure amplitude field has been done in a semi-anechoic chamber, with dimensions 5 x 3,3 x 3,5 m³ (57,75 m³). The semi-anechoic chamber has a reflecting floor and absorbing enclosures, as can be observed in Fig.4.18.

4.5.2- Experimental determination of the directivity pattern of an ultrasonic system

The main objective of the ultrasonic systems studied in this work is to generate a coherent ultrasonic radiation in free field. It has been proved that the application of steps in the surface of the radiator is essential in the generation of this field [89]. This surface treatment has been done in the APUT with circular radiator. Nevertheless, in order to improve the versatility of the transducer and to double the efficiency of the system (using both faces of the radiator), the system with a flat rectangular radiator and reflectors was developed with the steps built in them.

The directivity measurements have been done in an anechoic room located in the facilities of the Instituto de Tecnologías Físicas y de la Información “Leonardo Torres Quevedo”, CSIC, in Madrid (Spain). This chamber has operational dimensions of 7.5 x 5.5 x 5.5 m³ (226.9 m³). The cut-off frequency is 80 Hz, so the chamber behaves as free field above that frequency. All the enclosures of the chamber are covered with wedges made of a mineral wool, in order to maximize the absorbing surface inside the chamber. The acoustic properties of the chamber satisfy the requirements indicated in the Annex A of the Spanish standard UNE-EN-ISO 3745:2012: “Acoustics - Determination of sound power levels and sound energy levels of noise sources using sound pressure - Precision methods for anechoic rooms and hemi-anechoic rooms”, with the general procedure for the qualification of anechoic and hemi-anechoic rooms. The anechoic chamber can be observed in Fig.4.19.

Fig.4.18.- Semi-anechoic chamber for the experimental ultrasonic field determination.

The measurements were done with a 1/8" pressure microphone (GRAS 40DP) placed at a distance of 7.8 m, in the far field. The measurement setup is similar as the one considered in the ultrasonic field characterization (Fig.4.17), and for a low power excitation (20 W). The emitter in each case was bolted to a rotating structure capable to pivot in steps of one degree in order to measure the acoustic pressure generated by the emitter in a sector of 180°.

Fig.4.19.- Anechoic chamber for the directivity determination of the ultrasonic system.

4.6- Conclusion.

This Chapter 4 is focused on the description of the experimental methodologies of the completed characterization of APT transducers. This characterization consists of a low power characterization, stability tests, nonlinear dynamics characterization, experimental modal analysis and characterization of the generated ultrasonic field. This methodology will be applied in the next chapter to the two transducers under analysis in this work.

5.- DEVELOPMENT OF POWER ULTRASONIC SYSTEMS

5.1- Development of an airborne power ultrasonic transducer with stepped-grooved circular radiator.

The numerical simulation of the APUT with a circular radiator with a stepped-grooved circular radiator situated the operational mode with seven nodal circles at about 25.7 kHz. The estimated ultrasonic field is coherent, although it is not equal as the field generated by a piston. The numerical analysis indicated that there are minimum possibilities of modal interaction, but it is necessary to test the system experimentally in order to determine the effect of other nonlinear effects.

The experimental determination of the behavior of this transducer has been done under different operational conditions: low power determination in the impedance analyzer; dynamic analysis under high power regime; experimental modal analysis and acoustic behavior with the experimental determination of the generated ultrasonic field and of the directivity pattern.

5.1.1- Low power characterization of the APUT with circular radiator in the impedance analyzer.

The electrical properties of the APUT with stepped-grooved circular radiator, measured using an impedance analyzer (HP 4194A), are shown in Table 5.1, where the values of the bandwidth and the quality factor indicate a highly resonant system. The Bode plot with the admittance of the transducer, including the real part (Conductance (G)) and the imaginary part (Susceptance (B)) is shown in Fig. 5.1, where the bandwidth can be observed.

Table 5.1.- Electrical properties of the APUT with circular radiator.

Frequency (Hz)	Conductance (mS)	Impedance (Ω)	Bandwidth (Hz)	Efficiency (%)	Quality factor Q	C_0 (nF)	L_0 (mH)
25835	2.31	396	5.6	70.3	4613	5.8	6.5

The results of the low power characterization present an ultrasonic system with a high quality factor and a narrow bandwidth. This implies that this system is very efficient, but it is also prone to lose track when operating continuously under working conditions. The development of a good ultrasonic controller for tracking the resonance of the transducer, like the one presented in [95], is then essential for a good performance of the system.

5.1.2- Stability tests done over the APUT with circular radiator.

As explained in Chapter 4, the stability tests determine the possibility of a failure of the system due to fatigue. This test consists on keeping the transducer working continuously during long periods at an increasing power.

The stability tests carried out with the APUT with stepped-grooved circular radiator consisted on keeping the system working for long time (up to 100 hours) at different power levels in the range 20W-200W. For each test, the evolution of the resonance frequency, the power and the spectrum displayed on the oscilloscope have been all monitored. Additionally, temperature measurements have been done with an infrared thermometer FLUKE 62 mini, pointing the laser to sensitive areas like the ceramics, bolts or radiator. The summary of the final results at the end of each stability test is presented in Table 5.2, including the highest value of temperature obtained for each power supply.

Fig. 5.1.- Electrical response of the APUT with stepped-grooved circular radiator.

Table 5.2.- Stability tests of the APUT with circular radiator.

Power (W)	Frequency (Hz)	Voltage (V)	Current (mA)	Impedance Z (Ω)	Time (h)	Temperature (°C)
20	25832	105	167	640	5	23
50	25831	174	276	635	15	26
100	25827	251	396	634	25	32
150	25812	312	476	662	25	38
200	25761	348	590	590	114	57

Table 5.2 shows the stable behavior of the main electrical characteristics of the transducer at the different power applied and working for more than 100 hours in the higher power regime (about 200 W). The whole operation lasts more than 10^{10} cycles without any signs of ultrasonic fatigue or saturation. This number of cycles is much higher than $5 \cdot 10^8$, number considered as fatigue limit in our tests. Regarding the evolution of temperature, values up to 57 °C were found with the system

working in a high power regime, with electric supplies around 200 W. The maximum values of temperature were found in the ceramics.

The power capacity of the APU transducer with stepped-grooved circular radiator can also be observed in Fig. 5.2, which represents the relationship between the supplied excitation voltage and the electrical power.

Fig. 5.2.- Power capacity of the stepped-grooved circular plate transducer.

The experimental characterization of the power capacity of the transducer under analysis indicates that, up to 200 W, the transducer does not present symptoms of saturation. So, it can operate normally at this power.

5.1.3- Nonlinear dynamic characterization of the APUT with stepped-grooved circular radiator.

The next set of tests to carry out over the APU transducer with stepped-grooved circular radiator is the determination of its nonlinear behavior when applying high power. The nonlinear dynamics characterization has been done following the procedure explained in Chapter 4.3. The objectives of this characterization is to determine the possibility of the appearance of any of the nonlinear effects introduced in Chapter 2.3 when the ultrasonic system is working under operational conditions in a high power regime.

5.1.3.1- Nonlinear characterization under continuous operation regime

This first set of experiments tries to characterize the behavior of the transducer, apart from the stability tests presented in Chapter 5.1.2. These experiments consist on continuous loggings of the evolution of several variables that characterize the behavior of the transducer during operation of the system.

The first analysis is to determine how the temperature increases during a continuous operation of the transducer with supplies of 50 W, 100 W and 200 W, respectively. In this case, a thermocouple is placed near the transducer, pointing towards the joint between the bolt and the radiator. This point has been chosen for temperature measurements because the mechanical stress here is maximum, at this point, the extensional vibration of the mechanical amplifier is

transformed into the flexural vibration of the plate. The duration of the experiment has been two hours for each supply, with a data logging each 10 s. This evolution is presented in Fig. 5.3.

The temperature increases its value up to 38 °C in the ceramics. This could be a difficulty in the performance of the system, considering that the value measured during the stability tests reached 57 °C (see Table 5.2). Nevertheless, the operation of the transducer was stable during long time, not suffering extreme heating or noises. Therefore, this system can be considered suitable for continuous working at resonance with a power supply up to 200 W.

Fig. 5.3.- Evolution of temperature with the transducer working continuously with 50 W, 100 W and 200 W supply.

On the other hand, data loggings for a continuous operation allow the characterization of other magnitudes. For example, it can be observed how the resonance frequency is displaced during operation. Frequency shifts are directly related to a continuous exposure to high vibration levels, as well as the heating of the piezoelectric ceramics, the appearance of a hysteretic response and other nonlinear effects [103, 104, 106]. These frequency displacements can be observed in Fig. 5.4. The decrease of the resonance frequency is more notorious with higher electric power:

Fig. 5.4.- Evolution of resonance frequency with the transducer working continuously with 50 W, 100 W and 200 W supply.

There is other type of experiments to characterize the nonlinear behavior of the ultrasonic transducer under continuous operation regime. The electric supply changes its amplitude, mainly increasing the excitation voltage. This methodology allows another way to obtain the power capacity of the system, among other comparisons.

This experiment consisted on a continuous supply between 10 V and 350 V, in steps of 10 V each 10 minutes, and a logging of the electrical and mechanical magnitudes at each step. This methodology presented a similar power capacity of the system as Fig. 5.2.

An even more interesting comparison is the relationship between the electric intensity flowing through the system and the vibration velocity measured with the 1D laser vibrometer. According to the electrical and mechanical analogies (see Annex B), an APU transducer can be defined as a two-port network (or quadripole), with two electrical ports that are analogous to the two mechanical ones. Here, the electric intensity and the velocity of the vibration transmitted along the transducer are analogous. So, a linear relationship between these two magnitudes is expected.

As mentioned, the measurement of the velocity of the vibration has been done using a 1D laser vibrometer pointing towards an area of the radiator with maximum displacements. The vibrational shape of the stepped-grooved circular radiator consists on a flexural mode with 7 nodal circles. The vibrometer points the laser towards an area between two nodal circles, as it can be observed in Fig. 5.5. Here, the thermocouple is pointing towards the join between the bolt and the plate.

Fig. 5.5.- Measurement of the velocity of vibration with the 1D laser vibrometer.

The linear relationship between the electric intensity and the velocity of vibration measured in an area of the radiator with maximum displacement can be observed in Fig. 5.6.

Finally, the displacement amplitude evolution with the input voltage is presented in Fig. 5.7. This displacement was measured with the 1D laser vibrometer, as shown in Fig. 5.5. Fig. 5.7 also depicts the evolution of power with voltage, in a curve similar as Fig. 5.2. It can be seen that, up to 325 V, the displacement amplitudes increase almost linearly with voltage. On the other hand, it can be appreciated that the displacement don't have a linear evolution with power, but an asymptotic trend begins to appear. The maximum displacement obtained with this plate was 4.45 μm .

This initial set of experiments, based on the relationship of several magnitudes with the APU transducer working continuously in its operational mode, shows a normal behavior of the transducer, not experiencing major issues due to excessive heating of the components, and a normal relationship between the electrical and mechanical variables.

Fig. 5.6.- Relationship between electric current and vibration velocity.

Fig. 5.7.- Displacement evolution with voltage.

Further experiments based on frequency sweeps around resonance will give more information about the existence of other nonlinear effects.

5.1.3.2- Nonlinear characterization with frequency sweeps around resonance

Other sets of experiments, like frequency sweeps, permit the identification of some nonlinear effects like frequency shifts, hysteresis or frequency drops. The methodology of frequency sweeps has been explained in Chapter 4.3.2.2.

Before doing 2D frequency sweeps around resonance, it is useful to have a spectrum to locate the operational mode and other nearby modes. The identification of vibration modes is done by a wide range frequency sweep. The electric voltage supplied is low, 20 V, because other resonance modes will be excited during the sweep and we want to limit the amplitude of vibrations in those other modes, avoiding possible damages.

An initial 1D sweep between 10 kHz and 90 kHz permits the identification of areas with higher modal density. The mechanical and electrical magnitudes measured are the vibration velocity in a maximum displacement area (see Fig. 5.5), the current and the admittance.

The 1D frequency sweep has been done by increasing the excitation frequency between 10 kHz and 90 kHz, in steps of 1 Hz. The mechanical and electrical response measured with the characterization system is presented in Fig. 5.8, which represents the spectrum and a frequency zoom around the operational mode at 25.8 kHz.

The curves of vibration velocity show higher modal density between 20 kHz and 40 kHz, finding few natural modes at higher frequencies. The zoom around the operational mode, found at 25841 Hz, presents another mode near 29 kHz, more than 3 kHz away.

The values of vibration velocity and admittance are higher in the mode at 29 kHz, even if this is not the operational one because its shape of vibration is different from the shape of the natural mode at 25.8 kHz.

To fully characterize the dynamic behavior of the system, it is necessary to measure frequency drift due to the temperature increasing in the ceramics, as well as investigating the appearance of hysteretic effects and softening or hardening nonlinear responses at increasing excitation levels. The procedure of the frequency sweeps consists of incrementing the excitation frequency upwards and downwards in a narrow frequency band through resonance. The sweeps were repeated for increasing excitation voltage in increments up to 310 V. The experiments were carried out using a continuous wave excitation and a burst excitation signal. This allowed for distinguishing between

responses showing the frequency drift associated with heating in the piezoceramics (continuous wave excitation) and those associated with nonlinear dynamics of the transducer (where heating effects are eliminated by adopting burst excitation). Fig. 5.9 shows the results presenting the measured vibration velocity using the 1D laser vibrometer, pointing at a maximum displacement area of the plate (see Fig. 5.5), while

The evolution of the vibration velocity has an analogous behavior as the evolution of the electric current, as can be observed in Fig. 5.10.

The measured frequency shift between 150 V and 310 V excitation level is small (less than 15 Hz), which is negligible. The measured responses are highly linear, exhibiting symmetry near overlap in the forward and backward sweep responses and no evidence of a bending backbone curve that would signify a softening or hardening nonlinearity. Moreover, no hysteretic responses have been found, meaning that this is a very stable system.

Overall, the nonlinear characterization has shown a very stable transducer exhibiting no adverse influences of temperature, modal interactions or nonlinear responses.

5.1.3.3- FFT experiments with the APU transducer operating at high power regime

As mentioned in Chapter 2.3, transducers working at a high power regime (subjected to vibrations with high amplitude), may experiment some nonlinear effects like energy transfer to other modes or frequencies like higher harmonics or other frequencies with an arithmetic relationship with the resonance frequency (autoparametric excitation).

The measured time-domain signal can be transformed to its equivalent frequency-domain signal by applying the Fast Fourier Transform (FFT). In this case, the FFT analysis has been done with the transducer operating continuously at its operational mode around 26 kHz, and with different values of power supply, between 50 W and 300 W.

The frequency spectrums obtained for the excitation of 50 W and 300 W are presented in Fig. 5.11, where it can be observed how several harmonics up to 90 kHz appear, as well as other modes, with lower amplitudes. The second and fourth harmonics have high amplitude compared with the fundamental, at least for a supply of 50 W, so an important part of the energy is transferred to other modes. This effect is clearer for a lower supply than for a 300 W operation, where also part of the energy is transferred to harmonics and other modes but in a lower percentage. This behavior is similar as the one presented in [107] for a stepped rectangular plate, which presented higher harmonics at lower power supplies than at maximum power.

Fig. 5.11.- Spectra at the resonance frequency of the APUT with circular radiator.

5.1.4- Experimental modal analysis of the APUT with stepped-grooved circular radiator.

The final determination of the nonlinear behavior of the APU transducer with a stepped-grooved circular radiator is the experimental modal analysis (EMA) of the system. This determination has been carried out in the facilities of the School of Engineering of the University of Glasgow in 2016. The EMA has been done according to the procedure explained in Chapter 4.4.

An experimental modal analysis was performed to validate the numerical model, presented in Chapter 3.3. The experiments were carried out using a 3D laser vibrometer (Polytec), capable of measuring the vibration velocity in three orthogonal directions. The location of the transducer and the 3D laser vibrometer can be observed in Fig. 5.12.

The measurement process consists of defining a grid of measurement points on the surfaces of the ultrasonic vibrator and the radiating plate, sufficiently fine to identify accurately all the mode shapes in the measured frequency range. The vibration displacements in the three orthogonal axes are then measured at each grid point using the 3D laser vibrometer and these measurements are processed in ME'Scope modal analysis software in order to characterize the modes of vibration.

Fig. 5.12.- EMA of the APUT with stepped-grooved circular plate.

The points of the grid define a wire-mesh model of the device that is used in the modal analysis software (ME'Scope) to represent the vibrational shapes at each modal frequency. In this case, the cylindrical parts of the transducer like the steel case, which protects the Langevin-type sandwich and the mechanical amplifier, would require too many measurement points (or grid points) to look like cylinders in the model. Considering that the protective housing is not supposed to vibrate with the rest of the transducer because it is isolated from the rest of the constitutive elements, only four points in the perimeter were considered. In the case of the mechanical amplifier, also four points were defined considering that they are enough to identify flexural and torsional modes. For this reason, both the housing and the mechanical amplifier look like square prisms instead of cylinders in the model shown in Fig. 5.13. In this case, almost 300 grid points are defined for the circular plate transducer. The mesh defined in the circular radiator has been distributed in 8 diameters with 32 measurement points in each one (256 points in the radiator). The ultrasonic vibrator has 36 grid points. The grid for the whole transducer is shown in Fig. 5.13.

Fig. 5.13.- ME'Scope model of the APU transducer with circular plate.

Fig. 5.14 shows the spectral distribution of the modal frequencies in the range 0-90 kHz. It can be observed that there is not a high density of modes in the range, and the modes with higher amplitude are located between 26 kHz and 35 kHz. This representation is done in terms of CMIF (Complex Mode Indicator Function), a dimensionless magnitude used to plot the eigenvalues obtained from a FRF (Frequency Response Function).

Fig. 5.14.- Spectral distribution of modal frequencies of the circular plate transducer.

The frequency of the operational vibration mode is measured at 25842 Hz, with a difference less than 1 % from the FEM prediction of 26957 Hz (see Fig. 3.16). Although the other near modes show higher CMIF magnitude than the operational one, the required mode with 7 nodal circles appears at 25842 Hz, as can be observed in Fig. 5.15.

The closest mode frequency is measured at 25436 Hz, about 400 Hz from the operational mode frequency and a sufficient separation to avoid interaction between the two modes. This mode and the next closest in frequency are shown in Fig. 5.16. The closest mode at 25436 Hz (Fig. 5.16.b) consists on a flexural mode with seven nodal circles and two diameters. The other modes, separated several kilohertz's from the operational one, correspond to a number of nodal circles and diameters. The modal analysis also supports the conclusion from the FEM that no modal coupling should be expected in the plate radiator transducer in operation since the frequency separation of the modes is sufficient to ensure no modal interaction.

Fig. 5.15.- 7NC operational mode for the circular plate transducer at 25842 Hz.

5.1.5- Acoustic characterization of the APUT with stepped-grooved circular radiator.

The objective of this ultrasonic system, radiating from the stepped profile, is to generate a coherent field because of the half wavelength deep steps that have been applied to the radiating surface. As explained in Chapter 2.2.3, the steps provide the required acoustic delays to have an in-phase radiation and to have constructive interferences that imply a more effective radiation system.

The acoustic characterization of this transducer consists on the measurement of the ultrasonic field generated by the APU transducer with stepped-grooved circular radiator.

The experimental determination of the ultrasonic field generated by the APU transducer in the near and far field has been done following the procedure explained in Chapter 4.5.1. The ultrasonic field generated by this system under operational conditions is intended to have a sound pressure level higher than 150 dB at the operational frequency around 26 kHz. This SPL is very high even for the measurement transducer (1/8" pressure microphone GRAS 40DP), which is not able to stand amplitudes that extreme.

Because of this reason, a linear approximation has been done in the experimental determination of the acoustic field generated by the stepped-grooved circular plate transducer. The excitation level in all cases has been 20 W.

This first determination is the ultrasonic field generated by the transducer, shown in Fig.2.26, and with the axis orientation represented in Fig. 5.17.

Fig. 5.17.- Axis orientation for the experimental determination of the ultrasonic field generated by the APUT with stepped-grooved circular radiator.

Firstly, a 1D linear scan, taking sound pressure measurements each mm, along x-axis allows the location of the maximum and minimum values that appear in the near field. In Fig. 5.18, all these distances are identified. The x-axis represents the distance to the plate (the axis of the radiator), and the y-axis represents the microphone response in sound pressure amplitude obtained at each point.

The limit between the near and far field appears at 608 mm from the radiator. In the near field there are six distances that correspond to maximum values of pressure amplitude (21 mm, 56 mm, 109 mm, 151 mm, 235 mm and 340 mm). As mentioned before, the measurements have been done for an excitation of 20 W. The slices, in plane YZ, parallel to the surface of the plate, at each distance, are shown in Fig. 5.19.

Fig. 5.18.- Ultrasonic field along the axis of the radiator of the transducer.

Fig. 5.19.- 2D ultrasonic field in the plane YZ at different distances from the radiator.

The acoustic energy is concentrated at the axis, as it can be observed in Fig. 5.19. The central area is becoming bigger when separating from the transducer. The energy concentration at the axis reaches its maximum at the edge between the near and far field. Near the radiator, the acoustic energy is distributed in circles because the distribution of displacements is not homogeneous along the circular radiator, but there are areas with maximums and areas without displacements (nodal circles). So, near the radiator, the spherical propagation is negligible, and the shape of the vibration of the plate originates this acoustic distribution.

An axisymmetric view of the shape of vibration of the circular radiator, with the seven nodal circles, as well as a distribution of displacements along a radius of the radiator can be observed in Fig. 3.18 (corresponding with the numerical simulation of this magnitude). This figure illustrates the fact that the displacements are not homogeneous along the circular radiator and justifies the acoustic energy distribution in circles near the plate.

The ultrasonic fields in the planes XY and XZ (Fig. 5.20) have been also characterized. The maximums and minimums are perfectly identified in the near field, as well as the uniformity in the far field, but with much lower amplitude due to the air absorption at 26 kHz and spherical propagation of ultrasonic waves:

Fig. 5.20.- 2D ultrasonic field in perpendicular planes to the transducer radiation surface.

As can be observed in Fig. 3.40 and Fig. 3.41 for the numerical simulation; and in Fig. 5.19 and Fig. 5.20 for the experimental determination of the ultrasonic field, it can be stated that both methods show a good correlation, validating the model used in this case.

The experimental determination of the acoustic behavior of the APU transducer with stepped-grooved circular radiator proves that the system is capable of generating an ultrasonic field similar as the field generated by a piston (see Fig.2.10), with a distribution of maximum and minimum values in the near field and an energy concentration in the separation between the Fresnel and Fraunhofer zones. In the far field, the spherical propagation provokes a continuous decrease of the pressure amplitude for volume unit.

5.2- Development of an airborne power ultrasonic transducer with flat rectangular radiator and a reflectors system.

The second ultrasonic system designed, characterized and tested has been introduced in Chapter 2.4.2. This system is composed by an APU transducer with a flat rectangular radiator, and a system of reflectors for a coherent radiator. As explained before, there are two principal advantages of using a reflector system: minimize the mechanical problems suffered by stepped rectangular plates [107], and double the efficiency of the system by using the acoustic energy radiated by the two faces of the plate.

The numerical simulation of the APUT with a flat rectangular radiator situated the operational mode with twelve nodal lines at about 21 kHz. The estimated ultrasonic field generated by the system with reflectors (SWR) is coherent, although it is not equal as the field generated by a piston, and covers double area than a system without this type of reflectors. The analysis indicated that there are minimum possibilities of modal interaction but it is necessary to test the system experimentally in order to determine the affection of other nonlinear effects.

The experimental determination of the behavior of this transducer has been done under different operational conditions: low power determination in the impedance analyzer; dynamic analysis under high power regime; experimental modal analysis and acoustic behavior with the experimental determination of the generated ultrasonic field and of the directivity pattern.

5.2.1- Low power characterization of the APUT with flat rectangular radiator in the impedance analyzer.

The electrical properties of the APUT with flat rectangular radiator, measured using an impedance analyzer (HP 4194A), are shown in Table 5.3, where the values of the bandwidth and the quality factor indicate a highly resonant system. The Bode plot with the admittance of the transducer, including the real part (Conductance (G)) and the imaginary part (Susceptance (B)) is shown in Fig. 5.21, where the bandwidth can be observed, and the value of the compensation capacity, obtained applying Eq. B. 16.

Table 5.3.- Electrical properties of the APUT with flat rectangular radiator.

Frequency (Hz)	Conductance (mS)	Impedance (Ω)	Bandwidth (Hz)	Efficiency (%)	Quality factor Q	C_0 (nF)	L_0 (mH)
21097	1.60	625	1.59	80	13268	5.9	9.6

The results of the low power characterization present an ultrasonic system with a very high quality factor and a very narrow bandwidth. This implies that this system is very efficient, but it is also prone to lose track when operating continuously under working conditions. Nevertheless, the ultrasonic controller used with these transducers can keep the system operating in resonance even for transducers with very high quality factors.

The value of the inductance compensation has been determined and it can be applied physically in the impedance matching unit, or electrically, for characterization purposes, when using the Labview® characterization application.

Fig. 5.21.- Electrical response of the APUT with flat rectangular radiator.

5.2.2- Stability tests done over the APUT with flat rectangular radiator.

As explained in Chapter 4, the stability tests determine the possibility of a failure of the system due to fatigue. This test consists on keeping the transducer working continuously during long periods at an increasing power. The stability tests carried out with the APUT with flat rectangular radiator consisted on keeping the system working for long time (up to 100 hours) at different power levels in the range 50W-400W. For each test, the evolution of the resonance frequency, the power and the spectrum displayed on the oscilloscope have been all monitored. Additionally, temperature measurements have been done with an infrared thermometer FLUKE Mini 62, pointing the laser to sensitive areas like the ceramics, bolts or radiator. The summary of the final results at the end of each stability test is presented in Table 5.4, including the highest value of temperature obtained for each power supply.

Table 5.4 shows the stable behavior of the main electrical characteristics of the transducer at the different power applied and working for 100 hours in the higher power regime (about 400 W). The whole operation corresponds to $7.6 \cdot 10^9$ cycles without any signs of ultrasonic fatigue or saturation. This number of cycles is much higher than $5 \cdot 10^8$, number established as sufficient for fatigue tests for aluminum. Regarding the evolution of temperature, values over 50 °C were found with the system working in a high power regime, with electric supplies around 400 W. This power value is much higher than the expected working regime (between 250 W and 300 W). The maximum values of temperature were found in the ceramics.

The power capacity of the APU transducer with flat rectangular radiator can also be observed in Fig. 5.22, which represents the relationship between the supplied excitation voltage and the

electrical power. The experimental characterization of the power capacity of the transducer under analysis indicates that, up to 400 W, the transducer does not present symptoms of saturation. So, it can operate normally at this power.

Table 5.4.- Stability tests of the APUT with flat rectangular radiator.

Power (W)	Frequency (Hz)	Voltage (V)	Current (mA)	Impedance $ Z $ (Ω)	Time (h)	Temperature ($^{\circ}$ C)
50	21141	209	237	883	10	22
100	21140	293	343	847	25	23.3
200	21088	391	490	819	25	37
250	21080	452	566	778	50	43.3
300	21076	463	677	685	50	47.1
350	21071	492	727	697	50	49.5
400	21065	523	763	683	100	56.9

5.2.3- Nonlinear dynamic characterization of the APUT with flat rectangular radiator.

The next set of tests to carry out over the APU transducer with flat rectangular radiator is the determination of its nonlinear behavior when applying high power. The nonlinear dynamic characterization has been done following the procedure explained in Chapter 4.3. The objectives of this characterization is to determine the possibility of the appearance of any of the nonlinear effects introduced in Chapter 2.3 when the ultrasonic system is working under operational conditions in a high power regime.

Fig. 5.22.- Power capacity of the flat rectangular plate transducer.

The results obtained after experimental determination of the nonlinear dynamics of the transducer has been obtained using the new characterization system (see Annex G).

5.2.3.1- Nonlinear characterization under continuous operation regime

This first set of experiments tries to characterize the behavior of the transducer, apart from the stability tests presented in Chapter 5.2.2. These experiments consist on continuous loggings of the evolution of several variables that characterize the behavior of the transducer during operation of the system.

The first analysis is to determine how the temperature increases during a continuous operation of the transducer with supplies of 50 W, 100 W and 200 W, respectively. In this case, a thermocouple is placed near the transducer, pointing towards the joint between the bolt and the radiator. The duration of the experiment has been two hours for each supply, with a data logging each 10 s. This evolution is presented in Fig. 5.23.

Fig. 5.23.- Evolution of temperature with the transducer working continuously with 50 W, 100 W and 200 W supply.

The temperature does not suffer major increases during this period. This experiment, together with the temperature evolution obtained manually in the stability tests (Table 5.4), permits the discard of problems due to extreme heating.

On the other hand, data loggings for a continuous operation allow the characterization of other magnitudes. For example, it can be observed how the resonance frequency is displaced during operation (see Fig. 5.24). The decrease of the resonance frequency is more notorious with higher electric power.

The new system can carry out other type of experiments to characterize the nonlinear behavior of the ultrasonic transducer under continuous operation regime. These experiments consist on a data logging under continuous operation. In the data logging process, the electric supply changes its amplitude, mainly increasing the excitation voltage. This methodology is another way to obtain the power capacity of the system, among other comparisons.

This experiment consisted on a continuous supply between 20 V and 230 V, in steps of 10 V each 10 seconds, and a logging of the electrical and mechanical magnitudes at each step. The results confirmed the power capacity presented in Fig. 5.22.

Other comparison is the relationship between the electric intensity flowing through the system and the vibration velocity measured with the 1D laser vibrometer. According to the electrical and mechanical analogies, the electric intensity and the velocity of the vibration transmitted along the transducer are analogous.

Fig. 5.24.- Evolution of resonance frequency with the transducer working continuously with 50 W, 100 W and 200 W supply.

The measurement of the velocity of the vibration has been done using a 1D laser vibrometer pointing towards an area of the radiator with maximum displacements. The vibrational shape of the flat rectangular radiator consists on a flexural mode with 12 nodal lines (12|0). Maximum values of displacements can be found between the two central nodal lines. The vibrometer points the laser towards this area, as it can be observed in Fig. 5.25.

Fig. 5.25.- Measurement of the velocity of vibration with the 1D laser vibrometer.

The linear relationship between the electric intensity and the velocity of vibration measured in an area of the radiator with maximum displacement can be observed in Fig. 5.26.

Fig. 5.26.- Relationship between electric current and vibration velocity.

Finally, the evolution of displacements with the applied voltage can also be determined by measuring the vibration velocity (m/s) and converting it into displacements. This evolution is presented in Fig. 5.27, where it can also be observed the power evolution with voltage, in this case, up to 425 V, which is near 250 W. The maximum displacement obtained is 13.54 μm , and the evolution of displacements is almost linear with voltage.

Fig. 5.27.- Relationship between electric voltage and displacements.

This initial set of experiments, based on the relationship of several magnitudes with the APU transducer working continuously in its operational mode, shows a normal behavior of the transducer, not experiencing major issues due to excessive heating of the components, and a normal relationship between the electrical and mechanical variables.

Further experiments based on frequency sweeps around resonance will give more information about the existence of other nonlinear effects.

5.2.3.2- Nonlinear characterization with frequency sweeps around resonance

Frequency sweeps (see Chapter 4.3.2.2) permit the identification of some nonlinear effects like frequency shifts, hysteresis or drops. Before doing 2D frequency sweeps around resonance, it is useful to have a spectrum to locate the operational mode and other modes. The identification of

vibration modes is done by a wide range frequency sweep. The electric voltage supplied is low, 20 V, because other resonance modes will be excited during the sweep and we want to limit the amplitude of vibrations in those other modes.

An initial 1D sweep between 1 kHz and 90 kHz permits the identification of areas with higher modal density. The mechanical and electrical magnitudes measured are the vibration velocity in a maximum displacement area (see Fig. 5.25), the current and the admittance.

The 1D frequency sweep has been done by increasing the excitation frequency between 1 kHz to 90 kHz, in steps of 0.5 Hz. The mechanical and electrical response measured with the characterization system is presented in Fig. 5.28, which represents the spectrum and a frequency zoom around the operational mode around 21.1 kHz.

Fig. 5.28.- Wide frequency range response of the APU transducer with 20 V supply.

The curves of vibration velocity show a high modal density between 60 kHz and 70 kHz, and higher values of vertical vibration velocity displacement around 2.5 kHz and around 62 kHz. The operational mode has been identified at 21143 Hz, and other near modes appear at 19730 Hz, and 21911 Hz.

The electrical magnitude presented is the admittance, whose values are higher in the resonance modes. The value of the admittance in the operational mode at 21 kHz is lower than the values of admittance of others close modes.

To fully characterize the dynamic behavior of the system, it is necessary to measure frequency drift due to the temperature increasing in the ceramics, as well as investigating the appearance of hysteretic effects and softening or hardening nonlinear responses at increasing excitation levels.

The procedure of the frequency sweeps consists of incrementing the excitation frequency upwards and downwards in a narrow frequency band through resonance. The sweeps were repeated for increasing excitation voltage in increments up to 225 V. The experiments were carried out using a continuous wave excitation and a burst excitation signal. This allowed for distinguishing between responses showing the frequency drift associated with heating in the piezoceramics (continuous wave excitation) and those associated with nonlinear dynamics of the transducer (where heating effects are eliminated by adopting burst excitation). Fig. 5.29 shows the results presenting the measured vibration velocity using the 1D laser vibrometer, pointing at a maximum displacement area of the plate.

The measured frequency shift between 100 V and 225 V excitation level is only 5 Hz, which is negligible. The measured responses are highly linear, exhibiting symmetry near overlap in the forward and backward sweep responses and no evidence of a bending backbone curve that would signify a softening or hardening nonlinearity. Moreover, no hysteretic responses have been found, meaning that this is a very stable system.

Nevertheless, there is a slight effect due to heating of the ceramics, which leads to a very slight hardening nonlinearity that is turned to a softening effect when applying a burst excitation, limiting then temperature increases of the ceramics. The same trend has been found at the evolution of electric current, having a slight hardening effect with continuous excitation, turning to a softening behavior with bursts (see Fig. 5.30).

During the frequency sweep measurements, the temperature was also measured at the union between the flat rectangular radiator plate and the mechanical amplifier, and this remained stable at 22 °C through all the experiments.

Overall, the nonlinear characterization has shown a very stable transducer exhibiting no adverse influences of temperature, modal interactions, or nonlinear responses.

a) Continuous signal excitation

b) Burst excitation

Fig. 5.30.- 2D sweeps around resonance (current).

5.2.3.3- FFT experiments with the transducer operating at high power regime

One of the main concerns related to the operation of APU transducers is to know how much energy will be transferred to higher harmonics or if an autoparametric excitation can happen (see Chapter 2.3.3).

To evaluate the spectrum of the mechanical vibration of the APU transducer, a Fast Fourier Transform (FFT) can be carried out. This process consists on doing a frequency sweep upwards and downwards with a high excitation level, and transform the vibration velocity signal measured with the 1D laser vibrometer to the frequency domain by a FFT.

This sweep corresponds to a 1D sweep between 21110 Hz and 21140 Hz, in steps of 0.1 Hz and a continuous excitation signal with 350 V. The velocity spectra have been obtained in several stages of the upwards and downwards sweep: far from the resonance, increasing slope, decreasing slope and resonance. The exact points of the sweep where the spectrum has been determined are presented in Fig. 5.31.

Fig. 5.31.- Points for the spectrum determination.

The exact frequencies where the frequency spectra have been determined are specified in Table 5.5.

Table 5.5.- Excitation frequencies where the spectrum has been obtained.

Upwards sweep	P1	P2	P3	P4	P5	P6	P7
	21111,0 Hz	21113,9 Hz	21115,6 Hz	21116,5 Hz	21117,3 Hz	21119,4 Hz	21132,1 Hz
Downwards sweep	P8	P9	P10	P11	P12	P13	P14
	21133,0 Hz	21119,1 Hz	21117,0 Hz	21116,2 Hz	21115,7 Hz	21113,5 Hz	21110,4 Hz

So, during the sweep, the spectrum of the vibration velocity signal is transformed into the frequency domain to determine the energy transferred to other frequencies. The spectra obtained in points P4 and P12 are shown in Fig. 5.32.

a) P4. Spectrum at resonance, upwards (linear)

b) P4. Spectrum at resonance, upwards (dB)

a) P12. Spectrum at resonance, downwards (linear)

b) P12. Spectrum at resonance, downwards (dB)

Fig. 5.32.- Spectra at the resonance frequency.

It can be observed how energy is transmitted to harmonics up to 84 kHz, with amplitudes that are at least 20 dB less than the amplitude of the fundamental. This means that, even if there is energy transference to other modes, this amount of transferred energy is small to be considered as a crucial nonlinear effect.

On the other hand, there are frequencies below the operational one that are excited, but their amplitudes are also small compared to the amplitude of the working frequency. This implies that neither autoparametric excitation is expected for this system.

5.2.4- Experimental modal analysis of the APUT with flat rectangular radiator.

The final determination of the nonlinear behavior of the APU transducer with a flat rectangular radiator is the experimental modal analysis (EMA) of the system. This determination has been carried out in the facilities of the School of Engineering of the University of Glasgow in 2016. The EMA has been done according to the procedure explained in Chapter 4.4.

An experimental modal analysis was performed to validate the numerical model. The experiments were carried out using a 3D laser vibrometer (Polytec), which measures the vibration velocity in three orthogonal directions. The location of the transducer and the 3D laser vibrometer can be observed in Fig. 5.33.

Fig. 5.33.- Experimental modal analysis of the APU transducer with rectangular plate.

The measurement process consists of defining a grid of measurement points on the surfaces of the ultrasonic vibrator and the radiating plate, sufficiently fine to identify accurately all the mode shapes in the measured frequency range. The vibration displacements in the three orthogonal axes are then measured at each grid point using the 3D laser vibrometer and these measurements are processed in ME'Scope modal analysis software in order to characterize the modes of vibration.

The points of the grid define a wire-mesh model of the device that is used in the modal analysis software (ME'Scope) to represent the vibrational shapes at each modal frequency. In this case, the cylindrical parts of the transducer like the steel case, which protects the Langevin-type sandwich and the mechanical amplifier, would require too many measurement points (or grid points) to look like cylinders in the model. Considering that the case is not supposed to vibrate with the rest of the transducer because it is isolated from the rest of the constitutive elements, only four points in the perimeter were considered. In the case of the mechanical amplifier, also four points were considered taking into account that they are enough to identify flexural and torsional modes. For this reason, both the case and the mechanical amplifier look like square prisms instead of cylinders in the model. In this case, 448 grid points are defined for the rectangular plate transducer,

configured as 28 x 16 points on the plate surface. The ultrasonic vibrator has 56 grid points. The grid for the whole plate radiator transducer is shown in Fig. 5.34.

Fig. 5.34.- ME'Scope model of the APU transducer with rectangular plate.

Fig. 5.35 shows the spectral distribution of the modal frequencies in the range 0-90 kHz, particularly showing the high modal density in the 15-30 kHz range which contains the operational mode. A zoom in on a narrower range near the operational frequency (Fig. 5.35.b) contains the two closest modal frequencies identified in the FEM. This representation is done in terms of CMIF (Complex Mode Indicator Function), a dimensionless magnitude used to plot the eigenvalues obtained from a FRF (Frequency Response Function).

a) Spectrum between 1 kHz to 90 kHz

b) Zoom around the operational frequency

Fig. 5.35.- Spectral distribution of modal frequencies of the rectangular plate transducer.

The frequency of the operational vibration mode is measured at 21130 Hz, with a difference of less than 0.5% from the FEM prediction of 21049 Hz (see Fig. 3.34). Although the other near modes show higher CMIF magnitude than the operational one, the required mode with 12 nodal lines appears at 21130 Hz, as can be observed in Fig. 5.36.

Fig. 5.36.- 12NL operational mode for the rectangular plate transducer at 21130 Hz.

The closest mode frequency is measured at 21898 Hz, about 770 Hz from the operational mode frequency and a sufficient separation to avoid interaction between the two modes. This mode and the next closest in frequency are shown in Fig. 5.37. The mode at 19720 Hz (Fig. 5.37.a) consists on an extensional mode in the mechanical amplifier and a flexural mode in the rectangular plate (4|6), exactly matching the FEM predicted modal frequency and shape. The other close mode, at 21898 Hz is an extensional mode in the vibrator and a complex flexural mode in the rectangular plate (Fig. 5.37.b), again matching the FEM predictions. The modal analysis also supports the conclusion from the FEM that no modal coupling should be expected in the plate radiator transducer in operation since the frequency separation of the modes is sufficient to ensure no modal interaction.

5.2.5- Acoustic characterization of the APUT with flat rectangular radiator.

The objective of this ultrasonic system is to generate a coherent field using the acoustic radiation generated by the two faces of the rectangular plate. The system of stepped reflectors provides the delays required to have constructive interferences of the ultrasonic waves, and doubles the efficiency of the system by using the whole energy generated by the radiator.

The acoustic characterization of this transducer consists on the measurement of the ultrasonic field and the directivity pattern obtained with the two configurations, without and with the reflectors system.

5.2.5.1- Ultrasonic field generated by the APUT with flat rectangular radiator without and with a reflector system

The experimental determination of the ultrasonic field generated by the APU transducer without and with reflectors in the near and far field has been done following the procedure explained in Chapter 4.5.1. The ultrasonic field generated by this system under operational conditions is intended to have a sound pressure level higher than 150 dB at the operational frequency around

21 kHz. This SPL is very high even for the measurement transducer (1/8" pressure microphone GRAS 40DP), which is not able to stand amplitudes that extreme.

Because of this reason, a linear approximation has been done in the experimental determination of the acoustic field generated by the rectangular plate transducer and by the SWR. The excitation level in all cases has been 20 W.

A) Determination of the ultrasonic field generated by the APU transducer with a flat rectangular radiator without reflector system.

This first determination is the ultrasonic field generated by the transducer without the reflectors system, shown in Fig.2.30, and with the axis orientation represented in Fig. 3.32. Firstly, a 1D linear scan, taking sound pressure measurements each mm, along x-axis allows the location of the maximum and minimum values that appear in the near field. In Fig. 5.38, all these distances are identified. The x-axis represents the separation to the plate, and the y-axis represents the microphone response in volts, analogous to the sound pressure amplitude obtained at each point.

The limit between the near and far field appears at 1129 mm from the radiator. In the near field there are six distances that correspond to maximum values of pressure amplitude (38 mm, 131 mm, 300 mm, 478 mm and 601 mm). As mentioned before, the measurements have been done for an excitation of 20 W. The slices, in plane YZ, parallel to the surface of the plate, at each distance, are shown in Fig. 5.39.

Fig. 5.38.- Ultrasonic field along the axis of the radiator of the transducer.

Fig. 5.39.- 2D ultrasonic field in the plane YZ at different distances from the radiator.

The nodal lines can be observed easily, as the measurements are done in the near field, although they are losing resolution because of the spherical propagation of the waves. The last figure corresponds to the limit between the near and far field, observing a more homogeneous field in the slice.

It has been also characterized the ultrasonic field in the planes XY and XZ (Fig. 5.40). The maximums and minimums are perfectly identified in the near field, and also the uniformity in the far field, but with much lower amplitude due to the air absorption at 21 kHz and spherical propagation of ultrasonic waves:

Fig. 5.40.- 2D ultrasonic field in the perpendicular planes to the transducer's radiation surface.

As can be observed in Fig. 3.45 and Fig. 3.48 for the numerical simulation; and in Fig. 5.39 and Fig. 5.40 in the case of the experimental determination of the ultrasonic field, both methods show a good correlation, validating the model used in this case.

B) Determination of the ultrasonic field generated by the APU transducer with a flat rectangular radiator with a reflectors system.

Using the same methodology as the previous section, the ultrasonic pressure amplitude field generated by the SWR has been characterized. In this case, the considered radiating surface has been the coherent field coming out of the structure, once the ultrasonic waves have reflected in the structure and put in phase. The axis orientation is shown in Fig. 3.49. The identification of the near and far field is represented in Fig. 5.41.

Fig. 5.41.- Ultrasonic field in the axis normal to the radiating surface.

The limit between the near and far field appears at 2612 mm from the radiator. In the near field there are four distances that correspond to maximum values of pressure amplitude (0 mm, 248 mm, 419 mm, 549 mm, and 1083 mm). The slices, in plane YZ, parallel to the surface of the plate, at each distance, are shown in Fig. 5.42.

Fig. 5.42.- 2D ultrasonic field in the plane YZ at different distances from the radiator (SWR).

The ultrasonic field is more uniform after putting in phase the ultrasonic waves. The central line that appear for $X=0$ corresponds to a surface of the radiator. The field becomes more homogeneous when moving away from the surface. The field in the planes XY and XZ has been also determined in Fig. 5.43.

Fig. 5.43.- 2D ultrasonic field generated by an ultrasonic SWR in the perpendicular planes to the radiation surface.

The results obtained after the experimental determination reflect the improvements obtained when using the reflectors, confirming the expectations obtained in the numerical analysis.

5.2.5.2- Directivity pattern of the ultrasonic field generated by the APUT with flat rectangular radiator without and with a reflector system

The experimental determination of the directivity pattern of the ultrasonic field generated by the ultrasonic system with flat rectangular radiator without and with a reflectors system for coherent radiation has been done following the procedure presented in Chapter 4.5.2.

The measurements of the acoustic pressure have been taken with a 1/8" microphone, capable of measuring frequencies over the audible range. As indicated before, the ultrasonic system was supported by a rotating structure so that, instead of moving the microphone, in steps of 1° , along a semicircle with a radius of 7.8 m and centered in the ultrasonic system, only the ultrasonic generator rotates in steps of 1° . The acoustic pressure measurements for each angle compounds the directivity pattern of the ultrasonic system without and with reflectors.

The directivity of each system has been determined for the planes XY and XZ, following the directional specifications shown in Fig. 3.32 and Fig. 3.49, respectively. The results obtained after the measurement campaign are shown in Fig. 5.44.

The ultrasonic SWR shows a very directional behavior (Fig. 5.44.c and Fig. 5.44.d), similar as a piston, while the directivity of the rectangular radiator presents two main lobes with angles around 10° and -10° with the normal direction in the horizontal plane (XY plane).

With the acoustic characterization of the ultrasonic system without and with reflectors, it has been proved that the attachment of stepped reflectors to the APU transducer with flat rectangular radiator increases the global efficiency of the system and generates a coherent ultrasonic radiation in free field, putting in phase the ultrasonic waves generated by the transducer.

The experimental acoustic analysis has validated the numerical models, presented in Chapter 3 and confirmed the expected behavior of both configurations (without and with a reflectors system).

These experimental results demonstrate for the first time the ability to use mobile reflecting structures coupled to high power transducers to generate intense and coherent acoustic fields. The planar sheet-steps of these structures are mechanically attached to the planar displacement nodes of the vibrating surface of the plate, producing a coherent field.

The acoustic field obtained at different distances from the radiator is more homogeneous and with higher amplitude because the system uses the energy produced by both faces of the transducer when using the reflectors.

The whole ultrasonic system including the reflectors show a higher directivity than conventional APUTs, concentrating the acoustic energy in the axial direction, while the system without reflectors radiates the acoustic energy forming 10° angles with the axis.

This new system provides versatility to the plate-based transducers actuation as the mobile structures can be modified or replaced by others depending on the mode of vibration selected for each specific desired application.

a) Flat rectangular plate, plane XY, horizontal direction

b) Flat rectangular plate, plane XZ, vertical direction

c) Ultrasonic SWR, plane XY, horizontal

d) Ultrasonic SWR, plane XZ, vertical.

Fig. 5.44.- Directivity of the two ultrasonic systems.

Although the scope of this work does not include the use of this new system in food dehydration experiments, future research lines will test the performance of this ultrasonic system in real food dehydration experiments under different operational conditions like the nature of the samples to dehydrate, environmental conditions (temperature, humidity), or the use of an airflow in the process.

5.3- Design of an adaptive mechanical amplifier for rectangular radiators.

As mentioned in previous chapters, this type of transducers requires a high efficiency to provoke the desired effects in the media. This means that the electric power supplied to the system must be transformed into mechanical vibrations in the thickness mode of the Langevin transducer

minimizing the losses and that this vibration must be propagated to the radiator, obtaining maximum values of vibration displacement and velocity.

The previous designs are the result of years of research and the efficiency achieved is quite good. Nevertheless, the search of a more efficient system led us to analyze variations in the geometry of the different components of the transducer. In this case, a study of the shape of the union area between the mechanical amplifier and the rectangular radiator has been done, taking into account the geometry of the plate and shape of the vibrations in the operational mode.

This numerical and experimental analysis has been carried out with an APUT designed for this purpose. In this case, the design of the horn allows the addition of external adapters with different shapes. Each of the adapters can be bolted at the tip of the horn, to have different shapes at the union between the horn and the extensive radiator.

5.3.1- Design of the airborne power ultrasonic transducer

The basis of the transducer used for this task is the same as other configurations. The transducer is composed by a Langevin transducer, mechanical amplifier and a rectangular radiator, with smaller dimensions (220x50x10 mm) and a desired operational mode with two longitudinal nodal lines (0|2) at about 19 kHz. The mechanical characteristics of the different components are presented in Annex E.

The mechanical amplifier has been designed for an extensional mode at about 19 kHz. As indicated in Chapter 2.2.2, each cylinder of the horn has to be $\frac{1}{4}$ wavelength long. It is important to indicate that, for this analysis, the tip of the mechanical amplifier is an external adapted designed for this purpose. The adapters have different shapes and dimensions, but all of them have the same thickness. The quarter wavelength of the narrow section of the horn includes the adapter in each case. This means that the horn has been shortened by 10 mm, which is the thickness of all the adapters chosen.

The shape of the vibration of the three main components of the transducer are presented in Fig. 5.45, where it can be appreciated the thickness mode of the Langevin transducer, the displacement and amplification ratio of the mechanical amplifier (almost 8.5) and the operational mode of the rectangular plate.

The whole transducer vibrates in the desired operational mode at a frequency of 19149 Hz, as can be observed in Fig. 5.46. According to the numerical simulation, there are other eigenmodes at relatively near frequencies, like a flange mode at 18956 Hz, and other complex modes at 21014 Hz and 22746 Hz. The three modes have enough distance from the operational one to prevent a modal interaction, only the eigenmode at 18956 Hz may show a small risk, but these series of experiments are not taken under a very high power regime, and that hypothetical modal interaction is very unlikely. These undesired modes are presented in Annex F.

5.3.2- Numerical analysis of the configurations of the mechanical amplifier

For this work, a total of five different configurations of the mechanical amplifier have been studied. All the configurations differ in the shape and size of the tip of the mechanical amplifier. The five adapters have a thickness of 10 mm and the shapes chosen are circular, square, rectangular and rounded (two adapters with different size in this case). These shapes are introduced in Fig. 5.47.

Fig. 5.47.- Shape of the adapters for the mechanical amplifier.

Before building the transducer, the numerical analysis of each system provided information about its performance and about what size would be interesting to choose for each adapter.

The whole process of the numerical analysis is included in Annex F.3, where the results are presented. These simulations consisted of two steps. The first analysis is a parametric eigenfrequency analysis for each shape with different dimensions to know the evolution of the operational mode and other close modes when the size of the adapter. For the eigenfrequencies study, a short circuit condition has been considered, applying a constant voltage of zero at all electrical contacts of the ceramic disks.

The second analysis corresponds to the simulated mechanical performance of the transducer with each adapter. For this simulation, under the lineal regime, a voltage of 20 V has been considered, at the working frequency, which is slightly different for each configuration. The amplitude of displacements has been obtained as the maximum value in the rectangular radiator, while the handicaps due to high displacements, and reflected as mechanical stress, have been observed in the mechanical amplifier, in the radiator and in the bolt that joins the two elements, for all the cases. These comparisons are done with the normalized amplitude of displacements and mechanical stresses. The use of normalized values is justified by the fact that this is a comparative analysis to decide which size build for the experimental research.

According to the numerical study for each case, the following adapters have been built and proved experimentally:

- Adapter 1.- Adapter with a circular shape. External radius 10.5 mm.
- Adapter 2.- Adapter with a short-rounded shape. Rectangle with sides 18 mm x 14 mm and rounded ends with radius 9 mm.
- Adapter 3.- Adapter with a long-rounded shape. Rectangle with sides 18 mm x 26 mm and rounded ends with radius 9 mm.
- Adapter 4.- Adapter with a squared shape. Side of 25 mm.
- Adapter 5.- Adapter with a rectangular shape. Dimensions 27 mm x 21 mm.

5.3.3- Experimental analysis of the performance of a rectangular plate transducer with different configurations of the mechanical amplifier

As a result of the numerical study, the five adapters indicated previously have been selected for the experimental analysis. The adapters are sandwiched between the rectangular plate and the mechanical amplifier with a through-screw that is bolted to the horn. The pieces have a space, which is a circular hole with radius of 5.2 mm, enough for a M10 bolt to pass through. The thickness of the five adapters is 10 mm. The adapters, made of duraluminium 7022, can be observed in Fig. 5.48.

Fig. 5.48.- Adapters for the experimental analysis.

The geometrical and mechanical properties of the transducer can be observed in Annex F. This transducer, with the circular adapter can be observed in Fig. 5.49.

Fig. 5.49.- Airborne power ultrasonic transducer with circular adapter.

5.3.3.1- Response of the transducer in the impedance analyzer

The first analysis, done with the five adapters, has been taken with the impedance analyzer Hewlett-Packard 4194A. The impedance analyzer allows a full electric characterization of the ultrasonic system. This equipment applies low power to the system, enough to identify the eigenfrequencies and to characterize the electrical response of the transducer.

Fig. 5.50.- Impedance analyzer HP 4194A and the transducer with circular adapter.

Among the variables characterized with the impedance analyzer we can find the resonance frequency, conductance at resonance, impedance, bandwidth and Q factor. The values of these variables obtained for the transducer with each adapter are presented in Table 5.6.

Table 5.6.- Low power characterization of the transducer with different adapters

Adapter	Shape	Resonance frequency (Hz)	Conductance (mS)	Impedance (Ω)	Bandwidth (Hz)	Q factor	Efficiency (%)
Adapter 1	Circular	19291	2.83	338	7.3	2643	56.9
Adapter 2	Short-rounded	19289	2.73	346	6.4	3014	50.1
Adapter 3	Long-rounded	19173	1.58	550	9.8	1956	43.0
Adapter 4	Squared	19660	0.94	766	4.9	4012	39.9
Adapter 5	Rectangular	19536	0.51	1028	17.2	1136	21.0

According to the results obtained after this analysis, and presented in Table 5.6, the circular and short rounded adapters present the highest values of conductance and efficiency, while the squared adapter has the highest quality factor, even if other variables (conductance and efficiency) show low values. Further experiments will provide more information about the behavior of this system with each adapter.

5.3.3.2- Stability analysis of the transducer with different adapters

This second set of analysis consists on a stability test, in order to determine the behavior of the transducer when operating at high power for a long duration, in terms of both fatigue and modal interactions. The stability analysis has been carried out using the dynamic characterization system

introduced in Chapter 4.3.1.2, capable of performing this analysis without needing an external ultrasonic controller.

Before carrying out the stability tests, which determine the power capacity of each configuration, it is important to identify areas with higher warm up and to determine if this is an extreme heating that would lead to a failure due to fatigue of the transducer.

This exhaustive analysis has been carried out for the transducer with a circular adapter and the rectangular radiator. The system has been working continuously at its operational mode with a flexural vibration with two nodal lines in the plate, and exposed to an electric supply between 2 W and 20 W, during a period of about ten minutes for each supply.

The analysis of the evolution of temperature has been carried out by manual measurements using an infrared temperature sensor FLUKE Mini 62. The temperature measurements were done by pointing the sensor manually to 13 points along the whole transducer, covering the areas likely to warm up, like the ceramics (points 2-3) and the joints between the mechanical amplifier and the radiator (points 12-13). These points are indicated in Fig. 5.51.

Fig. 5.51.- Temperature measurement points.

The evolution of the temperature in all the 13 points during this experiment is presented in Fig. 5.52, where it can be observed how the higher heating happens in point 4, located in the area of the front mass closer to the ceramics stack, and in the ceramics themselves. Anyway, the maximum temperature measured at this point is 39 °C with an electric supply of 20 W, being a dangerous value of temperature.

The evolution of the temperature at the most affected areas (points 3, 4 and 5) of the transducer, working under its maximum power regime (20 W), was studied. The system was kept under operational conditions for almost 5 hours. The results are presented in Fig. 5.53.

It can be perfectly observed how the temperature at point 4 remains stable under 45 °C, without experiencing high temperature. The stability tests will confirm that the transducer is capable of working under a high power regime during long periods.

Fig. 5.52.- Evolution of temperature along the transducer.

The stability tests have been carried out for the five adapters considered in this analysis. This test consists on keeping the transducer working continuously during long periods at an increasing power. The stability tests consisted on keeping the system working for long time at different power levels in the range 0W-20W. For each test, the evolution of the resonance frequency, the power and the spectrum displayed on the oscilloscope have been all monitored. Additionally, temperature measurements have been done with an infrared thermometer FLUKE Mini 62, pointing the laser to sensitive areas of the transducer (point 4).

Fig. 5.53.- Temperature with the transducer working with a 20 W supply.

The comparison between the results obtained with the five adapters is presented in Table 5.7, where the maximum power tested appears, with the electric parameters derived from the electric excitation and the behavior of the transducer. According to Table 5.7, the circular adapter needs the lowest voltage supply to reach 20 W, followed by the short rounded adapter. On the other hand, the squared adapter is not capable of reaching 20 W even with a supply of 118 V. None of the adapters suffer from major heating even if they have been operating at its maximum desired power for more than 30 h:

Table 5.7.- Stability tests of the transducer with different adapters.

Adapter	Shape	Power (W)	Frequency (Hz)	Voltage (V)	Current (mA)	Impedance $ Z $ (Ω)	Time (h)	Temp ($^{\circ}\text{C}$)
Adapter 1	Circular	21	19285	90	232	388	16	42
Adapter 2	Short-rounded	20	19311	105	195	535	23	38
Adapter 3	Long-rounded	20	19271	130	156	832	25	32
Adapter 4	Squared	8	19636	118	69	1701	23	32
Adapter 5	Rectangular	20	19516	137	155	884	65	36

5.3.3.3- Dynamic analysis of the transducer with different adapters

The third set of experiments was carried out in the laboratory, using a dynamic characterization system based on a Labview application. The experiments taken with this characterization system were the following:

- The determination of the relationship between applied voltage and electrical power of the system working at its operational frequency.
- Evolution of the temperature value in the ceramics and other sensitive areas of the transducer when working long periods.
- 1 D sweep between 1 kHz and 90 kHz, to observe a mode distribution, and more detailed sweeps around resonance.
- 2 D sweeps around resonance, for different voltage values (between 1 V and 100 V).

The experiments that measure the mechanical displacements have been taken using the 1D laser vibrometer, pointing towards an area of the radiator with maximum displacement amplitude. In this case, this point is located between the two nodal lines, equidistant from the center and the edge of the plate. A small piece of non-reflecting tape was stuck in the place where the laser was pointing for two reasons; the first was to minimize the scattering of the reflected laser, and the second was to identify the exact area where the displacement measurements were done in all cases. The location of the laser in the plate is presented in Fig. 5.54, where the nodal lines can be identified using iron powder. This powder has been spilled along the surface of the radiator. When

the system vibrates, the powder is forced to move to areas with no displacement, which are the nodal lines.

Fig. 5.54.- Location of the displacement measurement point.

A.- VOLTAGE – POWER RELATIONSHIP

As mentioned before, the first analysis was the relationship between supplied voltage at the operational frequency and the power obtained in the transducer. This experiment consists on a continuous supply of electric voltage, increasing each minute its value from 10 V to 120 V in steps of 10 V, and obtaining the electric response of the transducer. Among the electric magnitudes analyzed, the electric power returned by the ultrasonic system provides good information about the efficiency of the system. The curves with the relationship between the supplied voltage and the returned power, for the five adapters studied, are presented in Fig. 5.55. Here, it can be observed how the transducer with a short-rounded adapter presents a better behavior because the electric power obtained is higher than the power obtained in the rest of configurations.

Fig. 5.55.- Relationship between supplied voltage and electric power.

B.- BROADBAND 1D SWEEP

The second analysis consists on a broadband 1D sweep (between 1 kHz and 90 kHz), and with a supplied voltage of 10 V. A 1D sweep analysis consists on a continuous voltage supply with variable frequency. In this case, the frequency changes between 1 kHz and 90 kHz, in steps of 1 Hz each 50 ms.

The magnitude analyzed with this 1D broadband sweep is the displacement magnitude, normal to the rectangular radiator, measured with a 1D laser vibrometer pointing at an area with maximum displacement.

The results obtained with the five adapters are presented in Fig. 5.56. The spectral behavior of the five configurations is similar, but some differences can be observed. There are several frequency bands with higher modal densities, like the area between 18 kHz to 28 kHz, or the area around 48 kHz. The maximum velocity amplitudes observed are about 150 mm/s, and they appear around 19.7 kHz (the operational frequency) and around 26.7 kHz:

Fig. 5.56.- Vibration velocity between 1 kHz and 90 kHz of the five configurations.

A zoom around the operational mode will give specific information about the location and amplitude of the operational mode. It can be observed in Fig. 5.57 how the adapters 4 and 5 locate the operational mode about 250 Hz away from adapters 1, 2 and 3. The maximum amplitude has been achieved by the short rounded adapter and the rectangular adapter. The closest modes are separated more than 1500 Hz, so, modal interaction is not expected for low excitation.

C.- 2D SWEEPS AROUND RESONANCE

The last set of experiments consists on a series of 2D frequency sweeps around resonance for different values of electric supply. The procedure for this type of tests consists of incrementing the excitation frequency upwards and downwards in a narrow frequency band through resonance. The sweeps were intended to be repeated for increasing excitation voltage in increments up to 100 V, using a burst excitation signal to eliminate heating effects from the experiments. Nevertheless, even if continuous operation experiments allowed an electric supply over 100 V, the response of the transducers with the five adapters suffered from instabilities over 40 V or 50 V, depending on the adapter considered. The results of the 2D sweeps experiments are presented in Fig. 5.58, where it can be observed how the energy of high electric supplies is lost, appearing holes where the peaks should be. This happens in all the configurations, and they are a symptom of parametric

excitation (see Fig.2.24, in Chapter 2.3.3). This energy leakage to other frequencies happens with supplies of 30 V or 40 V, depending on the adapter used in each case.

Fig. 5.57.- Vibration velocity between 18.5 kHz and 21.5 kHz of the five configurations.

a) Adapter 1. Circular

b) Adapter 2. Short rounded

c) Adapter 3. Long rounded

d) Adapter 4. Squared

e) Adapter 5. Rectangular

Fig. 5.58.- 2D sweeps around resonance of the five ultrasonic configurations.

5.3.4- Summary of the results obtained with the five configurations analyzed

According to the experimental characterization presented in this section, the use of mechanical amplifiers with different type of contact with the extensive radiator may provoke slight differences in the behavior of the APU transducers analyzed.

The study of the influence of the shape of the contacting area between the mechanical amplifier and the extensive radiator has been carried out numerically and experimentally. Five shapes have been chosen (circular, short rounded, long rounded, squared and rectangular), and manufactured for the experimental characterization. The size of each adapter has been selected by the numerical analysis of its behavior with the aid of the FEM software COMSOL Multiphysics.

The dynamic characterization has been carried out through a series of experiments, including a low power analysis with the impedance analyzer, stability tests and nonlinear characterization. Slight differences between the behaviors of each configuration have been found. These differences can be appreciated in Table 5.8, where some of the variables analyzed are presented.

As observed in Table 5.8, the circular and the short rounded adapters show the most efficient behavior when applying low electric supply (impedance analysis experiments), and in terms of power capacity. The configurations studied present similar nonlinear behavior, with the appearance of a parametric vibration when applying an electric supply over 30 V in frequency sweeps.

According to the results obtained from the experimental analysis of all the configurations, the short-rounded shape seems to be promising in terms of efficiency of the new system.

Future research trends should deepen on the design of new shapes in the contact between the mechanical amplifier and the extensive radiator.

Table 5.8.- Final results of the ultrasonic system with different adapters.

	Adapter	Adapter 1	Adapter 2	Adapter 3	Adapter 4	Adapter 5
	Shape	Circular	Short-rounded	Long-rounded	Squared	Rectangular
IMPEDANCE ANALYZER	Frequency (Hz)	19291	19289	19173	19660	19536
	Conductance (mS)	2.83	2.73	1.58	0.94	0.51
	Impedance $ Z $ (Ω)	338	346	550	766	1028
	Bandwidth (Hz)	7.3	6.4	9.8	4.9	17.2
	Efficiency (%)	56.9	50.1	43.0	39.9	21.0
	Quality factor	2643	3014	1956	4012	1136
LOGGING	Power (W) with 100 V supply	16	18	10	6	14
	Temp ($^{\circ}\text{C}$)	40	37	36	32	31
	Impedance $ Z $ (Ω)	400	500	750	1700	880
2D SWEEPS	Nonlinear behavior	Softening	Slightly hardening	Softening	Softening	Softening
	Maximum supply without parametric vibration (V)	30	30	30	30	30
	Vibration velocity (mm/s) with 30 V	500	700	580	550	690

5.4- Conclusion.

The transducers designed in Chapter 3 have been characterized applying the experimental methods presented in Chapter 4. This Chapter 5 presented the results of this characterization of the two transducers involved in this project. The performance of the two systems analyzed is correct for the purpose they were designed.

The APUT with stepped-grooved circular radiator has an operational mode with 7NC at a frequency of 25835 Hz and with high quality factor. The transducer was tested under maximum power for long periods without suffering from fatigue and the nonlinear characterization didn't show hints of undesired nonlinear effects apart from a slight softening effect. The experimental modal analysis confirmed the numerical conclusions indicating that this modal interaction is unlikely when applying high power.

The acoustic field generated by this transducer presented a coherent distribution, obtaining a behavior similar as a piston.

This full characterization of this transducer has been presented in the following publications:

- **Conference paper.** 2016. R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "Description of an ultrasonic technology for food dehydration process intensification," Proceedings of Meetings on Acoustics, vol. 28, p. 045003.
- **Congress presentation.** 2016. R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "New ultrasonic technologies for food dehydration process intensification," in 22nd International Congress on Acoustics (ICA), Buenos Aires (Argentina).
- **Congress presentation.** 2018. R. R. Andrés, V. M. Acosta, A. Pinto, and E. Riera, "Airborne power ultrasonic systems for food dehydration processes intensification," presented at the 25th International Congress on Sound and Vibration, Hiroshima (Japan).

The APUT with flat rectangular radiator presented an operational mode with 12NL at a frequency of 21097 Hz and a very high quality factor (more than 13000). The behavior of the transducer under a high-power regime has been proved to be correct without the expectation of suffering from undesired nonlinear effects. On the other hand, the system with reflectors is capable of generating a high-intensity acoustic field covering a wider area than the transducer without reflectors. The analysis of the behavior of this transducer has been published in

- **Journal paper.** 2018. R. R. Andrés, V. M. Acosta, M. Lucas, and E. Riera, "Modal analysis and nonlinear characterization of an airborne power ultrasonic transducer with rectangular plate radiator," Ultrasonics, vol. 82, pp. 345-356, 2018/01/01.
- **Journal paper.** 2019. R. R. Andrés, A. Pinto, I. Martínez, and E. Riera, "Acoustic field generated by an innovative airborne power ultrasonic system with reflectors for coherent radiation," Ultrasonics, p. 105963, 2019/07/15.
- **Conference paper.** 2015. R. R. Andrés, A. Blanco, V. M. Acosta, E. Riera, I. Martínez, and A. Pinto, "New ultrasonic controller and characterization system for low temperature drying process intensification," Physics Procedia, vol. 70, pp. 833-836.
- **Conference paper.** 2016. E. Riera, V. M. Acosta, J. Bon, M. Aleixandre, A. Blanco, R. R. Andrés, et al., "Airborne Power Ultrasonic Technologies for Intensification of Food and Environmental Processes," Physics Procedia, vol. 87, pp. 54-60, 2016/01/01.
- **Congress presentation.** 2017. R. R. Andrés, V. M. Acosta, and E. Riera, "Ultrasonic field generated by different airborne power ultrasonic transducers with extensive radiators," in Tecnicacústica 2017: 48^o Congreso Español de Acústica. A Coruña 3-6 Octubre.

Finally, an initial study of the effect of the shape of the mechanical amplifier has been done obtaining a promising result for an adaptor with long rounded shape, placed in parallel with the nodal lines of the rectangular plate. This work produced two congress presentations:

- **Congress presentation.** 2016. R. R. Andres, V. M. Acosta, O. Louisnard, and E. Riera, "Effect of the design of the mechanical amplifier in the behavior of a high power ultrasonic transducer," in Euroregio 2016, Porto (Portugal).
- **Congress presentation.** 2017. R. R. Andrés, E. Riera, and A. Pinto, "Study about the influence of the shape of a horn in the mechanical behavior of an airborne power ultrasonic transducer with rectangular radiator," in UIA Symposium, Dresde (Germany).

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6.- AIRBORNE POWER ULTRASOUND FOR DRYING PROCESSES INTENSIFICATION AT LOW TEMPERATURE: USE OF A STEPPED-GROOVED PLATE TRANSDUCER

6.1- Introduction.

The reduction of water content is one of the main ways to achieve food preservation. This is the case of convective drying of solids, where product moisture is transferred to a gas media such as air. The mass transfer process in these solid-gas systems is influenced by both internal and external resistance. Internal resistance results from the characteristics of the solid matrix and temperature while external resistance mainly depends on the boundary layer thickness [144]. Currently, convective hot-air drying (CHAD) is one of the most common and widely used drying techniques used to extend the shelf life of food products. However, this is a highly time and energy consuming thermal process [145], which also negatively affects the final quality properties of the dehydrated product such as color, texture, flavor, rehydration capacity, content of vitamins or other nutrients [144].

Airborne power ultrasound application in drying systems may overcome some of the limitations of CHAD by increasing the drying rate without significantly affecting the quality of the final product. Ultrasound wave propagation mainly produces mechanical effects in the treated medium that can intensify the water removal without producing a significant heating of samples [46-48, 146]. In fact, APU has been widely investigated in food processing applications [43, 54, 69, 89, 140, 147-152] with the goal of increasing the drying rate of materials. Specifically, ultrasonically assisted CHAD process permits the use of lower temperatures and may be useful for drying heat sensitive materials [47].

In 2017 Cárcel et al.[54], published a very interesting work on ultrasonically assisted CHAD that shows how the properties of the material structure being drying affect APU application. For this purpose, a quantitative analysis of the drying kinetics of orange peel, lemon peel, eggplant, apple, cassava, potato, and carrot samples were carried out at 40 °C and 1m/s with different ultrasonic powers from 0 to 75W in Valencia by the ASPA Group. It was observed that the slope of the linear relationship, between the effective diffusivity and the level of APU application, depended on the product being dried. Thus, the structure not only determine porosity and textural properties (softness and hardness), but also the acoustic transmission coefficient in the product sample. In other words, it controls acoustic propagation, the energy losses at the interface gas-solid, and consequently, the energy available in the solid matrix of the sample for water removal. Cárcel says that porosity can be used to estimate the feasibility of applying APU in a CHAD processes.

Generally, the ultrasonic energy is used to produce permanent changes in the treated medium. Its use is based on the adequate exploitation of a series of mechanisms activated by the high-intensity ultrasonic waves, such as radiation pressure, acoustic streaming, agitation, instability at the interfaces and structural diffusion [149], see Annex A. In this way, when a high-intensity

ultrasonic wave propagates in a medium in the presence of obstacles, continuous radiation forces that act on said obstacles give rise to what is known as radiation pressure. The radiation pressure is linked to any wave process and has its origin in the change of moment that the wave experiences when acting on an obstacle. These forces are intense for high-power ultrasonic waves giving rise to processes of drag and interaction [47]. As the ultrasonic absorption processes on the high-intensity waves, radiation forces are generated inducing movements to the irradiated fluid, improving the transfer of matter and heat [148].

In addition, high-intensity ultrasound produces pressure variations in the solid-gas and liquid-gas interfaces that may influence the rate of evaporation/sublimation (as a function of temperature) of the solvent molecules retained in the matrix. During the negative phase of the pressure cycle, the pressure of the solvent at the solid surface decreases, enhancing its transport to the surrounding fluid. The high-intensity ultrasonic energy also causes oscillating and microcurrent velocities at the interface that may contribute to the decrease the thickness of the diffusion boundary layer [153, 154]. This reduces the external resistance to the matter transfer increasing the mass transfer coefficient.

The effects of ultrasound at the interfaces can also influence in the internal resistance to matter transport when they affect the intercellular spaces inside the matrix. These phenomena will be more intense in those materials with a wide network of intercellular spaces [148]. When the ultrasonic energy propagates through the solid, semi-solid or liquid matrix, it causes rapid series of alternative contractions and expansions. This process could be similar to what happens when a sponge is squeezed and relaxed, so it is usually known as microsp sponge effect [47, 142, 155]. These alternate stresses facilitate the movement and elimination of the solvents (like water) through the microscopic channels created by the propagation of the wave, increasing the diffusion coefficients. Therefore, the mechanical effects produced by ultrasound can induce an improvement in the mass transfer phenomena, which can involve both drying time and energy costs shortens. A relevant characteristic of high-intensity ultrasonic waves is their capacity to work synergistically with other forms of energy in order to promote, accelerate, or improve many processes. This is the reason why many practical applications of high power ultrasound are not exclusively ultrasonic processes but ultrasonically assisted processes.

As mentioned before, the use of power ultrasound to assist food dehydration processes allows the acceleration of the processes even at lower temperatures. The following sections will be focused on atmospheric freeze drying (AFD). AFD process corresponds to a lyophilization at atmospheric pressure. Traditional lyophilization process or conventional freeze drying is a food dehydration method that consists on the sublimation of the ice located inside food samples. This sublimation is enhanced by lowering the pressure around the samples, even under vacuum conditions, according to Fick's laws of diffusion. The pressure difference between the samples and its surroundings stimulates the delivery of the moisture content into the medium. This is a very effective process but with a high operating cost due to the energy consumption required by the vacuum equipment [156]. AFD processes do not need the energy consumption of the vacuum equipment. Moreover, the use of PU to accelerate this process implies a modification of the traditional lyophilization, by modifying the surroundings to an environment with atmospheric

pressure. A gas medium is necessary for the propagation of the ultrasonic waves. So, this process is known as lyophilization at atmospheric pressure, or AFD, assisted by power ultrasound.

As indicated in Chapter 1.4.2, APU may be considered a promising technology for enhancing the AFD process, although the use of cylindrical radiators may not be enough for an industrial scaling-up of the process. Hence, it is necessary to study the influence of other geometries capable of covering wider volumes and higher amount of food. These geometries are the two APU transducers presented in this document: an APU transducer with a stepped-grooved circular radiator and an APU transducer with a flat rectangular plate and a system with reflectors.

This chapter deals with the development, integration and testing of the latest ultrasonic technologies developed by the USTG group-CSIC and commercialized by PUSONICS SL and the experimental results of their implementation in a pilot scale drier in the ASPA group-UPV facilities. This system is composed of a convective drier and an airborne power ultrasonic transducer with a stepped circular radiator for the generation of a coherent field. The performance of this new system was evaluated by a study of drying kinetics of apple samples, dehydrated under different operational conditions.

6.2- Materials and methods.

6.2.1- AFD drier with APU application by stepped circular plate radiator (SCPR)

The drier, designed to carry out ultrasonically assisted AFD experiments, consists of a semi-industrial freezing chamber (Fig. 6.1) divided in two sections, a pre-chamber and the drying chamber. The pre-chamber allows constant temperature and relative humidity in the drying chamber. This constant relative humidity is achieved by recirculating air from the drying chamber through a bed of desiccant material. The drying temperature was maintained at the desired level by a combination of the evaporating system of the freezing chamber and an electrical resistance. The temperature and relative humidity sensors (Rotronic iroflex, mod. HYGROFLX HF520DB1) allowed the monitoring both parameters. A fan provided a flat air flux whose velocity was measured with an anemometer. The air flux is directly focused towards the sample holder. A scale registered changes in the weight of samples during drying. A Labview application was developed to control the process conditions (temperature, air velocity) inside the drying chamber.

The principal elements inside the chamber are the airborne power ultrasonic transducer and the weighing scale. The first component generates the ultrasonic field that provokes the desired effects in the food samples, while the second checks the evolution of the drying process by measuring the weight of the samples. The transducer used in these tests corresponds to an airborne power ultrasonic transducer with stepped-grooved circular radiator, whose operational mode has seven nodal circles at around 26 kHz.

The transducer needs an electric supply and the guidelines to vibrate at the required frequency with the desired amplitude. Outside the chamber lies the signal generation system, composed by a dynamic resonance frequency control unit (ultrasonic controller), to give adjustable continuous power output at the resonance frequency of the transducer by keeping the voltage (V) and current (I) signals in phase, and tracking it when this frequency shifts during operation [95, 137]. The

controller operates as a finely tuned electronic signal generator that sends the excitation signal to a broad-band power amplifier and then to the transducer through an impedance matching unit to allow maximum energy transfer between the electronics and the transducer.

The electrical response of the transducer can be measured at the output of impedance matching unit by sampling the voltage and current signals, which are sent back to the controller. The display of the controller returns the information about voltage, current, power, impedance, frequency and phase.

Fig. 6.1.- Representation of the dehydration chamber.

The environmental variables (temperature, relative humidity and air flow velocity) inside the chamber are logged in a computer using a Labview application designed for this purpose. The most adequate humidity value inside the chamber is as close to zero as possible, because the dehydration process follows the Fick's diffusion laws, meaning that there is a transfer of the wet content from places with higher amount of water to places with smaller amount of water. If the humidity, or wet content, in the environment is zero, it is easier for the water inside the food sample to move outside. Silica gel is a good water adsorbing material, so, this is a good solution to keep low values of humidity. A forced air circulation inside the chamber transport the wet air through a deposit of silica gel where the water is adsorbed, returning dry air into the chamber. This silica deposit is presented in Fig. 6.2.

The Labview application also allows selecting of the desired value of temperature inside the chamber, and the velocity of the air flow generated by a small fan, and which flows through the food samples to improve the dehydration process. This air flow must not be confused with the forced air circulation.

Finally, the way to determine the evolution of the dehydration process is by weighing the food samples. The samples are composed by a solid matrix and water. The solid matrix experiences no major changes in this process, but the wet content is being transferred to the media. So, the weight of the sample decreases continuously because the wet content disappears by sublimation. A weighing scale is placed inside the chamber to weight the samples in intervals of about 15', and sends the data to the computer to be processed with the Labview application. The dehydration kinetics is represented as the evolution of the weight of the food samples along the operation time.

Fig. 6.2.- Silica deposit for the adsorption of the humidity in the dehydration chamber.

Fig. 6.3.- View of the dehydration chamber from the antechamber.

The lyophilization at atmospheric pressure process takes place inside a chamber where the environmental variables are kept under the desired limits. The facility is composed by the chamber and an antechamber, which is isolated from the outside. The chamber has dimensions 1000x1080x1570 mm, and can be accessed from the antechamber through two gates, as shown in

Fig. 6.3. The transducer hangs from an aluminum profile through a rod, facing the tray where the samples are placed.

6.2.2- Acoustic properties of the dehydration chamber

The analysis of the ultrasonic field generated inside the dehydration chamber may be useful to find the most effective configuration of the APU transducer, and to know which areas present a higher concentration of the acoustic energy, supposedly associated to areas with a more effective process. The characterization of the ultrasonic field has been done numerically and experimentally, as presented in the following sections.

6.2.2.1- Numerical characterization of the acoustic properties of the dehydration chamber

The numerical characterization of the ultrasonic field generated inside the dehydration chamber has been done using the Finite Element Method with the software COMSOL Multiphysics®. The basis of FEM, as well as its application in Multiphysics and Acoustics simulations has been explained in Chapter 3. This initial simulation has been carried out with two main objectives:

- **The determination of the most effective location of the APU transducer.** As shown in previous paragraphs, the APU transducer is hung inside the dehydration chamber, with the stepped profile of the circular radiator pointing downwards, where the food samples are placed. The distance between the samples and the radiator has been defined by a parametric analysis done for different values of separation between them.
- **The definition of the pressure distribution in the samples area.** This second result defines where the acoustic energy is higher, because this area is supposed to be where the lyophilization process is faster.

The simulation carried out corresponds to a Multiphysics simulation with the Solid Mechanics physics that defines the vibration of the circular radiator and the Pressure Acoustics physics that obtains the pressure distribution inside the dehydration chamber.

The nature of this simulation depends utterly on the geometry of the lyophilization chamber. As indicated in the previous section, the chamber is a cabinet with dimensions 1000x1080x1570 mm. The transducer and the food samples are placed on a side of the cabinet, with a separation from all the walls higher than 25 cm.

A 3D simulation requires much higher computational resources than a 2D axisymmetric simulation. On the other hand, the 2D axisymmetric model permits a finer mesh, which can be associated with a more accurate result. Considering the axisymmetric nature of the APU transducer, it would be preferable this model, but it is necessary to find out how affects the surrounding acoustic energy in the field generated between the radiator and the samples.

Hence, neglecting the effects of the reverberation inside the cabinet, the lateral boundaries of the 2D axisymmetric model have been defined as perfectly matched layers (PML's) to simulate a free propagation in that direction, while the front boundary, where the samples are placed, is defined with a reflecting material, Polystyrene, with a specific acoustic impedance of $Z=35100$ Rayls, between the impedance of a sound hard boundary ($Z=\infty$) and of a sound soft

boundary ($Z=0$). The 2D axisymmetric model of this simulation is presented in Fig. 6.4, where the transducer can be appreciated, as well as the different boundaries. The blue area corresponds to the PML of the lateral and back boundaries, the green line corresponds to the symmetry axis, and the red line is the place where the samples are located, defined as a polystyrene material:

Fig. 6.4.- 2D axisymmetric representation of the model of the drying chamber.

An initial simulation consists of the determination of the most efficient separation between the radiator and the samples. A parametric analysis for different values of this separation has been carried out. This Multiphysics simulation consists of a mechanical vibration of the circular radiator at its operational frequency, considering an initial prescribed displacement at the basis of the bolt of $10\ \mu\text{m}$. The vibration of the plate generates an ultrasonic field in the surrounding medium.

The decision of the most efficient separation between radiator and samples comes from the calculation of the acoustic pressure existent in the area where the samples are placed (highlighted in red in Fig. 6.4). Integrating the acoustic pressure obtaining along this line for each simulation, we can define the most efficient configuration. The results are presented in Fig. 6.5.

Fig. 6.5.- Integrated acoustic pressure (N/m) for each separation between radiator and samples.

According to Fig. 6.5, the most efficient separation between the radiator and the food samples is about 19 cm. So, this is the separation considered for the experimental determination of the acoustic field and for the food dehydration experimental campaign.

The ultrasonic field generated by the radiator, working at its operational frequency, inside the dehydration area is presented in Fig. 6.6.a and Fig. 6.6.b, while the pressure distribution in the area where the samples are placed is presented in Fig. 6.6.c and Fig. 6.6.d.

Fig. 6.6.- Ultrasonic field generated by the stepped circular radiator in the dehydration area.

The ultrasonic field obtained has a very high energy concentration, with amplitudes higher at the axis and in the central area of the basis where the samples are placed. The shape of the ultrasonic field are consequent with the observations by Beranek regarding the acoustic behavior of circular radiators following Bessel functions [10]. The amplitude of the ultrasonic pressure obtained in this area reaches up to 160 dB in some places.

This numerical simulation will be validated by an experimental campaign to determine the ultrasonic field inside the dehydration cabinet, as presented in the following section.

6.2.1.2- Experimental characterization of the acoustic properties of the dehydration chamber

The validation of the numerical results presented in the previous section has been done by the experimental characterization of the acoustic field generated by the APU transducer with the stepped circular radiator.

The axisymmetric behavior of the transducer and the neglecting of the effects of reverberation inside the drying cabinet permit the simplification of the measurements to a plane delimited by the axis of the transducer, a radius of the radiator and the basis where the samples are placed. The experimental determination of the ultrasonic field has been done using a 1/8" microphone GRAS 40DP, connected to a signal adapter B&K NEXUS 2690 that supplies the polarization voltage of 200 V to the microphone, necessary for its correct performance. The NEXUS system is connected to a PC by a RS232 series port. The measurements are sent to an oscilloscope TEKTRONIX MDO3024 and then to the PC, where they are processed with a Labview[®] application developed for this purpose.

Apart from processing the results of the measurements, this application also drives the NEXUS signal adapter. The inputs of the application are the measurement file in the time domain, generated by the oscilloscope and the input and output parameters of the NEXUS. The output data are the frequency spectrum and sound pressure level (in dB) obtained at each measurement point. The measurement chain for this characterization is presented in Fig. 6.7.

The ultrasonic controller allows the APU transducer to operate at the desired mode, even if its associated resonance frequency displaces slightly (mainly to lower frequencies). In this case, the APUT works in a mode with seven nodal circles at a frequency around 26 kHz. The amplitude of the electric power supplied to the transducer is also defined by the ultrasonic controller. The power supplied in this experiment is 50 W because:

- The microphone has a maximum admissible sound pressure amplitude around 170 dB. According previous simulations, an electric power around 50 W is capable of generating an acoustic field with an amplitude about 150 dB.
- An electric supply of 50 W implies a certain grade of nonlinear behavior in the ultrasonic field, so the results obtained can be escalated to a supply of 200 W with a lower grade of error than the error obtained if the measurements were done for a lower supply.

A power amplifier supplies the required power without overloads in the excitation system. And, finally, the impedance matching unit adapts the impedance of the electric system to the impedance of the transducer, which is about 600 Ω in resonance.

The APUT is placed inside the freeze drying cabinet, where the lyophilization at atmospheric pressure experiments are carried out, under the desired environmental conditions: temperature about -15 °C, atmospheric pressure and relative humidity as low as possible.

As mentioned before, an axisymmetric behavior of the system is supposed. Hence, the acoustic measurements have been done in two different planes covering the area between the axis, radiator and basis. Different measurements have been done for each plane, obtaining a mean value.

Each plane has dimensions of 20x19 cm, in which a mesh has been defined, with measurement points separated 4 mm in both directions, axial (Z) and radial (R). The APUT works in the desired mode with 7 nodal circles at around 26 kHz. This implies that the acoustic wave has a wavelength higher than 13 mm. A mesh with 4 mm between measurement points guarantees at least three points each wavelength. Each measurement lasts 15 s, obtaining a linear average for the whole period in each measurement.

Fig. 6.7.- Scheme of the measurement chain for the experimental determination of the ultrasonic field generated by the stepped circular radiator inside the drying cabinet.

The 1/8" microphone gets the acoustic signal at each point. The behavior of the microphone is linear up to 40 kHz, as it can be observed in Fig. 6.8. The measurement system is presented in Fig. 6.9. It can be observed how the microphone is placed forming a 90° angle with the measurement plane (and the direction of propagation of the ultrasonic wave). In this case, according to the directivity pattern of the microphone, for a 26 kHz wave, the correction to apply in this case is less than 1 dB, so it can be neglected.

The measurement system is composed by a trolley that leans on the existing metallic profiles and which allow horizontal displacements. Another trolley hangs from the horizontal one, allowing vertical displacements. At the bottom of the vertical trolley, a stepper motor is placed to allow the vertical displacement of the trolley. A horizontal arm is bolted at the bottom of the vertical trolley and the microphone is stuck at the end of this arm.

Due to constructive characteristics of the measurement system, the microphone could not be placed closer than 5 cm from the transducer. The other side of the measurement corresponds to the basis where the samples are placed. The measurements were done in vertical lines, displacing

the arm with the microphone, step by step, up to 4 mm between measurement points. Once the vertical line was finished, a horizontal displacement of the trolley, by manual means, was done, up to 4 mm, in order to cover the 4 mm mesh defined previously.

Fig. 6.8.- Frequency behavior of the 1/8" microphone GRAS 40DP.

Fig. 6.9.- System for acoustic measurements.

The stepper motor used for automatic vertical displacements, McLennan 23HSX-206, was driven by a Labview® application developed for this purpose and integrated into the measurement application so that the displacement of the vertical trolley was coincident with the processing of the previous acquisition.

The Labview® application developed for these measurements included all aspects like the definition of the parameters of the B&K NEXUS signal adapter (output sensibility), acquisition of the data obtained by the TEKTRONIX oscilloscope, signal processing to obtain the broadband SPL, sound pressure level around 26 kHz and the spectrum of the signal. This application also drove the trolley displacement with the aid of the stepper motor, as it has been previously mentioned.

The measurement plane mentioned previously had a surface of 20x19 cm. Considering that the closest the microphone could get to the radiator was 4 cm, the effective measuring surface was 20x15 cm. This implies a mesh with almost 2000 measurement points (1989 points). The acoustic distribution in an axisymmetric plane, obtained experimentally for a power supply of 50 W, is presented in Fig. 6.10.

Fig. 6.10.- Ultrasonic field generated by the stepped circular radiator in the dehydration area.

As obtained in the numerical simulation of the acoustic field inside the chamber, the APU transducer was placed inside the dehydration chamber, 19 cm above the sample holder. As a result, the volume covered by the transducer in terms of acoustic efficiency was 0.0239 m^3 and the surface, 0.126 m^2 . The experimental acoustic characterization indicates that for an electric excitation of 50W to the APU transducer, the sound pressure level (SPL) achieved in the volume of interest is 147 dB (547 W/ m^2). More specifically, the SPL obtained in the area where the food

samples were placed was 148 dB (582 W/m^2). The acoustic energy is concentrated at the axis of the transducer, obtaining a SPL of 152 dB (1421 W/m^2) in this area.

The experimental results obtained after the measurement campaign and presented in Fig. 6.10 validate the numerical model whose results are presented in Fig. 6.6, in terms of distribution of the acoustic energy.

The experimental characterization of the acoustic field allowed the confirmation of the nonlinear behavior of the system. The ultrasonic field generated by the APU transducer with stepped circular radiator, working under a power supply of 50 W, can experience a number of nonlinear effects both in generation and in propagation of the acoustic signal, with the appearance of harmonics of the fundamental. The results obtained in two points indicated in Fig. 6.10.b are presented in Fig. 6.11, both in the time and frequency domains. These two points corresponds with a high acoustic pressure area (P1) and an area in the axis with a lower acoustic pressure (P2).

Fig. 6.11.- Nonlinear effects in the ultrasonic field measured inside the drying cabinet.

Depending on the grade of nonlinearity, the observed harmonics have higher or lower amplitude. Point 1 corresponds to an area with higher acoustic amplitude, probably because the nonlinear effects are less evident, the time signal appears as a sine and the amplitude of the harmonics is small. In point 2, the signal in the time domain is deeply affected by the existence of harmonics. There is also an important loss of energy in this area.

Following sections are focused on the dehydration processes that take place inside the presented drying cabinet.

6.2.3- Drying kinetics. Numerical model

Mathematical models are always good tools for prediction, optimization, characterization and analysis of processes. These models can be divided into theoretical and empirical models [157]. Theoretical models give useful information about the mechanisms that take place in the process and are developed from the physical principles to quantitatively describe a process. Empirical models are obtained through mathematical or statistical analysis of experimental data to describe the process.

The diffusional theory is the most common model to describe dehydration processes. In this case, an empirical model, based on the Fick's second law of diffusion, was used to describe the low temperature dehydration processes done experimentally. The Fick's laws of diffusion describe diffusion and can be used to solve for the diffusion coefficient, D_e . Fick's second law predicts how the concentration change with time due to diffusion [158]. The resulting drying kinetics was modeled to quantify the influence of the conditions tested using a model based on the Fick's law. Because of the geometry of samples used (slices), the mass transport was assumed as unidimensional (Eq.6.1).

$$\frac{\partial W_p(x, t)}{\partial t} = D_e \left(\frac{\partial^2 W_p(x, t)}{\partial x^2} \right) \quad \text{Eq.6.1}$$

Where W_p is the local water content ($kg_{water} / kg_{dry\ matter}$), x represents the water transport characteristic direction (m), t is drying time (s) and D_e represents the effective diffusivity of moisture (m^2/s), meaning a measurement of the inverse of the internal mass transfer resistance. It was considered that this effective moisture diffusivity was constant, no shrinkage occur and the solid samples were homogeneous. This last fact is not completely correct in atmospheric freeze drying conditions because during the process two main parts can be distinguished in the samples: an external dried layer, which increases during the process, and an internal frozen core, which decreases. Nonetheless, this model has been previously used [57, 58] with the aim to quantify process variables influence on drying kinetics. The Eq.6.1 is a second order partial derivative equation with respect the mass transport direction (x) and first order with respect drying time (t). According to this, an initial condition and two boundary conditions have to be considered to solve the equation:

- The initial moisture content (W_0) is the same in all points of the solid (Eq.6.2):

$$W_p(x, 0) = W_0 \quad \text{Eq.6.2}$$

- No net moisture transport occurs at the symmetry plan of the solid (Eq.6.3):

$$\frac{\partial W_p(0, t)}{\partial x} = 0 \quad \text{Eq.6.3}$$

- The moisture transported from the inner to the surface of the sample by diffusion is transferred to the drying air by convection (Eq.6.4):

$$-D_e \rho_{ss} \frac{\partial W_p(L, t)}{\partial x} = k((L, t) - \varphi_{air}) \quad \text{Eq.6.4}$$

Where ρ_{ss} is the dry solid density ($\text{kg}_{\text{dry matter}}/\text{m}^3$), k is the mass transfer coefficient ($\text{kg}_{\text{water}}/\text{m}^2\text{s}$), a_w is the water activity at the sample surface and φ_{air} is the relative humidity of the air flow. The value of the water activity (a_w) at each moment can be estimated by solving the equation of the model of GAB, presented in Eq.6.5:

$$W = W_m \frac{C_G K_G a_w}{(1 - K_G a_w)(1 + (C_G - 1)K_G a_w)} \quad \text{Eq.6.5}$$

Where W is the average water content ($\text{kg}_{\text{water}} / \text{kg}_{\text{dry matter}}$), W_m is the water content in the monolayer, C_G is the heat of sorption in the monolayer and K_G is the heat of sorption in the multilayer.

This model was numerically solved by a finite difference method using MATLAB 7.11.0. For this, D_e and k identified values minimized the square differences between experimental and calculated moisture content of samples [159].

6.3- Experimental campaign.

6.3.1- Raw material and moisture content

Apples (Granny Smith var.), similar in size (approximate weight of 250 g), color (light green), and ripeness (10.5^{-12} Brix), were purchased from a local market (Valencia, Spain). This variety of apple was chosen because of its homogeneity. With the help of a mandolin, slices 3mm thick were taken from the fleshy part of the apples, avoiding the area of the apple core. Then, samples were introduced in a waterproof bag to prevent moisture content changes and were frozen in a blast freezing system (Hiber, mod. 051S) at a temperature of -35°C for 1 hour. After that, drying experiments were carried out.

a) Samples for the determination of the water content of apple slices. b) Vacuum oven.

Fig. 6.12.- Determination of the initial moisture content.

Initial moisture content of the samples was determined following the AOAC standard method no. 934.06 [160]. For this, fresh apple samples (5 g approx..) were placed in a vacuum oven at 70°C

and 200 mm Hg until a constant weight was achieved. The samples are weighted in a precision scale before and after this complete drying. If the operational conditions of the vacuum oven are correct, the weight loss is because of the removal of the wet content, and only the solid matrix remains. This initial experiment determined the percentage of water of the food samples. For this determination, six samples of 5 gr of the same apple were used, as it can be observed in Fig. 6.12, as well as the vacuum oven where they were placed. The value of the moisture content is obtained using the average of the six samples. In this case, 86% of the composition of apples “Granny Smith” is water, and this is the maximum weight reduction available. In terms of relationship between the existent water and dry matter in the samples, the initial moisture content of apple was $6.14 \pm 0.13 \text{ kg}_{\text{water}}/\text{kg}_{\text{dry matter}}$.

The $a_w(L, t)$, necessary for the numerical model, was estimated from the sorption isotherm reported by Vega-Galvez et al. [161], which model GAB parameters (W_m , C_G and K_G) are showed in Table 6.1.

Table 6.1.- Parameters used for the drying kinetics modelling.

Parameter	Value
Thickness	3 mm
L	1.5 mm
Drying temperature (T)	-12 °C
φ_{air}	0.05
W_m	0.18 $\text{kg}_{\text{water}} / \text{kg}_{\text{dry matter}}$
C_G	8.9
K_G	0.89
ρ_{ss}	800 kg/m^3

6.3.2- Atmospheric freeze-drying experiments

The AFD experiments were conducted at a constant velocity of air flow (1 m/s) and relative humidity below 7 %. Varying parameters considered for the experiments were different grades of temperature, between -3 °C and -17 °C, and variations in the applied ultrasonic power, with experiments without (0 W) and experiments with at 3 different levels of electric power applied to the transducer (50 W, 100 W, 200W). Each run was conducted with fifteen samples that mean an initial mass load ranging from 80 g and 100 g. The different drying conditions were tested, at least, in triplicate and drying was extended until samples lost at least 80% of the initial weight.

The experimental process consisted on placing the apple samples inside the drying cabinet, and starting the drying process under the desired environmental conditions of the chamber and operational conditions of the transducer. The weight of the samples was measured at the beginning of the experiment and each 15 minutes, approximately. Assuming that the weight reduction corresponds to losses of the amount of water of the food samples, the evolution of this parameter defines the drying kinetics for each experiment. The location of the apple samples and the transducer inside the dehydration chamber is shown in Fig. 6.13.

A summary of the experiments carried out under different circumstances are presented in Table 6.2. The basic parameters indicated are the date of the experiment, mean temperature and relative humidity inside the drying chamber during the experiment, the electric power applied to the transducer, the parameters that define the kinetics of the experiment and the time required to reach a weight loss of 80% of the initial.

Fig. 6.13.- Setup for the dehydration experiments.

Table 6.2.- Freeze drying experiments carried out in the dehydration chamber.

Test	Date	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m^2/s)	Mass transfer k (kg_{water}/m^2s)	Time of the experiment (min)
1	2018_06_20	0W	-2.8	5.7	1.07E-10	3.99E-04	574
2	2018_06_15	0W	-3.3	0.5	1.13E-10	2.13E-04	554
3	2018_06_18	0W	-3.3	1.5	6.68E-11	2.28E-04	554
4	2018_10_11	0W	-2.6	3.7	9.02E-11	2.57E-04	451
5	2018_06_29	0W	-13.2	0.8	3.14E-11	1.76E-04	1435
6	2018_07_13	0W	-13.2	0.5	3.78E-11	1.60E-04	1496
7	2018_07_04	0W	-13.4	7.1	3.81E-11	1.59E-04	1476
8	2018_10_05	0W	-12.9	3.1	3.05E-11	8.38E-05	1312
9	2018_05_14	0W	-17	0.5	1.10E-11	8.84E-05	2282
10	2018_05_09	0W	-17.1	4.8	1.49E-11	7.50E-05	1992
11	2018_05_17	0W	-17.1	0.5	1.13E-11	7.49E-05	2319

Test	Date	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m ² /s)	Mass transfer k (kg _{water} /m ² s)	Duration experiment (min)
12	2018_04_19	0W	-17.7	9.7	1.27E-11	5.19E-05	2697
13	2018_06_08	50W	-12.1	2.9	2.34E-11	1.45E-04	1066
14	2018_07_27	50W	-12.7	4.7	3.73E-11	1.90E-04	1128
15	2018_07_17	50W	-12.7	3.6	4.59E-11	1.60E-04	1086
16	2018_06_01	50W	-13.8	2.3	2.50E-11	1.24E-04	1209
17	2018_05_25	50W	-14.1	2.2	2.23E-11	1.15E-04	1353
18	2018_06_12	100W	-6.9	1	7.31E-11	1.84E-04	594
19	2018_06_04	100W	-7.9	1.7	5.35E-11	1.65E-04	615
20	2018_06_14	100W	-9.7	0.8	4.84E-11	1.60E-04	718
21	2018_07_24	100W	-12.1	0.3	3.80E-11	1.86E-04	922
22	2018_05_23	100W	-12.3	2.9	3.60E-11	1.32E-04	923
23	2018_06_25	100W	-12.3	3.7	5.00E-11	2.56E-04	943
24	2018_05_21	100W	-12.6	1.2	2.81E-11	1.27E-04	1087
25	2018_05_28	150W	-7.8	1.9	9.48E-11	1.85E-04	574
26	2018_05_31	150W	-8.5	1.9	9.37E-11	1.89E-04	574
27	2018_05_30	150W	-9.6	0.2	5.31E-11	1.95E-04	615
28	2018_07_09	150W	-11.8	2.7	5.38E-11	2.80E-04	882
29	2018_07_20	150W	-12	6.7	5.21E-11	3.34E-04	984
30	2018_06_13	200W	-3.6	0.3	8.84E-11	2.56E-04	410
31	2018_06_11	200W	-4	0.7	1.41E-10	2.42E-04	410
32	2018_06_07	200W	-6.8	0.9	1.36E-10	1.87E-04	533
33	2018_06_06	200W	-9.3	0.2	5.85E-11	2.15E-04	574
34	2018_06_26	200W	-11.2	2.3	4.29E-11	3.28E-04	840
35	2018_06_27	200W	-11.4	5.2	4.52E-11	3.11E-04	840
36	2018_07_02	200W	-11.6	2.9	6.64E-11	3.12E-04	759

As shown in Table 6.2, 36 valid experiments have been done, for different environmental conditions and of supplied power. The values of temperature and relative humidity correspond to the mean value obtained during the whole experiment. The effective diffusivity coefficient (D_e) and the mass transfer coefficient (k) were identified by fitting the proposed model (Eq.6.1) to the experimental data (Table 6.2). As stated before, the partial frozen state during drying invalidate the homogeneous condition of the samples considered to solve the model. This fact becomes this theoretical model in an experimental one. However, the inverse of D_e and k parameters identified provided a measurement of the influence of drying condition tested on both, internal and external mass transfer resistance, respectively.

The experiments have been grouped depending on different criteria like similar electric power and temperature during the process. A further comparison between the results allows us to determine the influence of the power applied to the transducer and of the temperature obtained inside the drying cabinet. These groups are shown in Table 6.3. The values of the different variables presented in the table correspond to the mean values of temperature and relative humidity and the result of the numerical modelling of the mean of the experimental curves obtained in the experiments indicated in the first column.

Table 6.3.- Data for the evaluation of the dehydration parameters.

Tests	Code	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m ² /s)	Mass transfer k (kg _{water} /m ² s)	Duration (min)
1, 2, 3, 4	NoUS_-3°C	0W	-3.0	2.9	7.77E-11	2.21E-04	533
5, 6, 7, 8	NoUS_-13°C	0W	-13.2	2.9	2.42E-11	8.69E-05	1450
9, 10, 11, 12	NoUS_-17°C	0W	-17.2	3.9	1.35E-11	1.05E-04	2300
13, 14, 15	50W_-12°C	50W	-12.5	3.7	3.35E-11	1.76E-04	1100
16, 17	50W_-14°C	50W	-14	2.3	2.60E-11	1.44E-04	1283
18, 19, 20	100W_-8°C	100W	-8.2	1.2	6.52E-11	1.83E-04	633
21, 22, 23, 24	100W_-12°C	100W	-12.3	2	3.46E-11	1.58E-04	967
25, 26, 27	150W_-9°C	150W	-8.6	1.3	8.21E-11	2.07E-04	583
28, 29	150W_-12°C	150W	-11.9	4.7	4.20E-11	2.38E-04	933
30, 31	200W_-4°C	200W	-3.8	0.5	1.23E-10	2.64E-04	417
32, 33	200W_-8°C	200W	-8.1	0.6	8.64E-11	2.10E-04	550
34, 35, 36	200W_-11°C	200W	-11.4	3.5	4.31E-11	2.29E-04	800

The influence of the temperature and of the supplied electric power in the freeze drying experiments carried out over Granny Smith apple slices has been analyzed. The results and conclusions obtained after these experiments are presented in the following sections.

6.4- Results and discussion.

As mentioned before, the influence of the drying temperature and of the electric power applied to the APU transducer with stepped circular radiator have been studied.

It is important to mention that the value of temperature considered in each experiment corresponds to the mean temperature of the whole process. The temperature sensor is placed in the chamber, just besides the APUT. The application of power ultrasounds in this process may imply the generation of heat in the propagation medium and, of course, in the samples due to the induced sponge-effect mentioned previously, which provokes the agitation of the product's molecules. Hence, the temperature measured inside the dehydration chamber may be lower than the temperature in the apple samples. Even in the set of experiments at temperatures about -3 °C, the real temperature in the samples may be over the freezing point of water. So, the temperature value should be considered as a mere reference.

The results for the lyophilization at atmospheric pressure experiments presented in the following subsections correspond to the dehydration kinetic curves and for the values of the defining parameters (effective diffusivity coefficient (D_e) and mass transfer coefficient (k)), obtained numerically by modelling the dehydration curves and fitting them with the model curves.

6.4.1- Influence of the applied electric power in the drying kinetics

6.4.1.1- Experiments at about -12 °C

The analysis of the influence of the applied electric power in drying kinetics has been done for a set of experiments at about -12 °C, as indicated in Table 6.4.

Table 6.4.- Data for the analysis of influence of the applied power.

Tests	Code	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m ² /s)	Mass transfer k (kg _{water} /m ² s)	Duration (min)
5, 6, 7, 8	NoUS_-13°C	0W	-13.2	2.9	2.42E-11	8.69E-05	1450
11, 12, 13	50W_-12°C	50W	-12.5	3.7	3.35E-11	1.76E-04	1100
19, 20, 21, 22	100W_-12°C	100W	-12.3	2	3.46E-11	1.58E-04	967
26, 27	150W_-12°C	150W	-11.9	4.7	4.20E-11	2.38E-04	933
32, 33, 34	200W_-11°C	200W	-11.4	3.5	4.31E-11	2.29E-04	800

The experimental results showed that the AFD of the apple samples was as slow process. Thus, the samples dried without ultrasound application needed 24.2 ± 1.4 h to reach an 80% initial weight loss (a moisture content of 1.23 kg_{water}/kg_{dry matter}). The application of ultrasound significantly accelerated the dehydration process being the greater the shortening of process the higher the electric power applied to the ultrasonic transducer. For example the drying time needed to reach an 80% initial weight loss for 50W experiments was 24% lower than the needed for 0 W experiments while 45% for 200 W experiments (see Table 6.5). It's important to highlight that the influence of ultrasound applications was important even at the low ultrasonic power applied 50 W.

The values of the effective diffusivity coefficient (D_e) and mass transfer coefficient (k) have been obtained by modelling the experimental dehydration kinetics (-12°C and 1 m/s) of apple assisted by APU with different power (0, 50, 100 and 200 W). In Table 6.5, $\Delta\%$ represents the percentage of increase of each parameter compared to non-ultrasonically assisted experiments (0W), or decrease in the time required to reach a final weight of 80%. The dried apple samples did not suffer major changes in its aspect, as it can be observed in Fig. 6.14.

Table 6.5.- Dehydration coefficients by modelling experimental AFD kinetics.

Ultrasonic power applied									
	0 W	50 W	Δ%	100 W	Δ%	150 W	Δ%	200 W	Δ%
D _e (10 ⁻¹¹ m2/s)	2.60±0.4	3.35±1.1	29	3.46±0.9	33	4.20±1.6	40	4.31±1.3	66
k (10-4 kgwater/m2 s)	1.12±0.1	1.76±0.2	57	1.58±0.6	41	2.38±1.0	63	2.29±0.1	104
Drying time (h)	23.6±0.5	18.3±0.5	22	16.1±1.3	32	15.6±1.2	36	13.3±0.8	44
Correlation coefficient. (%)	99.4	99.8		99.9		99.9		99.9	
Explained variance (%)	99.3	99.8		99.9		99.9		99.9	
Mean relative error. (%)	14.5	7.6		2.7		4.9		2.2

Fig. 6.14.- Apple samples before and after the dehydration process.

The representation of the drying kinetics under the five operational conditions analyzed (Fig. 6.15) permits the comparison between the experimental (dots) and modelled (lines) curves at each case. Thus, it can be observed that the modelled drying kinetics fitted adequately the experimental results and both, experimental and calculated curves followed the same trend. It must be highlighted that this trend was more similar in experiments carried out with ultrasound application (50, 100, 150 and 200 W) than in non-ultrasonically assisted ones (0 W).

Fig. 6.15.- Experimental and calculated moisture evolution during drying apple slices (-12 °C).

The accuracy of the model fitting was quantified by three parameters: the correlation coefficient, the explained variance and the relative mean error (see Table 6.5). As indicated previously, the highest relative error (14.5 %) was obtained for the case on drying kinetics without the use of ultrasound. In the case of ultrasonically assisted experiments, the higher the electric power applied to the transducer, the lower the relative mean error (except the tests at 150 W, where the number of experiments were lower, increasing the deviations). It seems that ultrasound application during AFD reduced the variability of results. This fact was observed before by García-Pérez et al [55] in ultrasonically assisted AFD by using cylindrical transducer. Even so, the correlation coefficient and the explained variance were higher than 99 % in all the drying conditions tested.

The values identified of D_e and k (Table 6.5) confirms the influence of the application of APU to enhance AFD processes. Ultrasound application increased both parameters being this increase higher the higher the electric power supplied to the ultrasonic system. Thus, compared to 0 W experiments, the D_e increased 29% in 50 W experiments while 66 % in 200 W ones. These results indicated the ultrasonic power applied was enough to induce significant effects in the internal moisture transport resistance of apple, even at the lowest electrical power applied to the transducer.

Similar influence of ultrasound application was observed for the k parameter. Thus, the value identified in 50 W experiments was 57 % higher than the identified in experiments carried out without ultrasound application while 104 % in the case of 200 W experiments.

It is important to mention that these results correspond to initial experiments with this new prototype of drier and provided with a power ultrasonic transducer with stepped circular radiator. The D_e and k values obtained in 0 W experiments were slightly lower, but in the same range, than those reported by Santacatalina et al. [57] during drying cubic apple samples (Granny Smith, var.) at -10 °C without ultrasound application ($3.5 \pm 0.4 \cdot 10^{-11} \text{ m}^2/\text{s}$ and $1.6 \pm 0.2 \cdot 10^{-4} \text{ kg}_{\text{water}}/\text{m}^2\text{s}$,

respectively) fitting the same model. When they apply ultrasound with a cylindrical transducer (50 W of electrical input) they observed 500 % increase in the D_e identified, being this value greater than the 58% increase observed in 200 W experiments of the present study. In the case of k , the increase produced by ultrasound application found by Santacatalina et al. [57] was 148% while in the present 200 W experiments was 86%. This comparison indicates that the cylindrical radiator seems to be more efficient than the stepped circular radiator because the increases of D_e and k values were much higher, applying less electric power to the ultrasonic transducer.

This fact is consistent because the acoustic energy generated by the cylindrical radiator is confined inside it. There, the small volume makes the acoustic energy to be concentrated in cells [46], as shown the acoustic distribution measurements. As indicated in previous chapters, the acoustic energy generated by the stepped circular radiator presents a more or less coherent distribution in free field, and inside the dehydration chamber, where the energy is concentrated along the axis of the radiator. Moreover, the acoustic energy in this case is not confined, and the volume covered by the transducer is much higher. Therefore, this system is not as efficient as the cylindrical radiator. However, the experimental results obtained proved that this new system may significantly improve the drying rate and can be used in an industrial scale.

6.4.1.2- Experiments at about -8 °C

A second analysis of the influence of the applied power has been done over experiments carried out at around -8 °C. The experiments considered in this analysis are those indicated in Table 6.6.

Table 6.6.- Data for the analysis of influence of the applied power at -8 °C.

Tests	Code	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m ² /s)	Mass transfer k (kg _{water} /m ² s)	Duration (min)
18, 19, 20	100W_-8°C	100W	-8.2	1.2	6.52E-11	1.83E-04	633
25, 26, 27	150W_-9°C	150W	-8.6	1.3	8.21E-11	2.07E-04	583
32, 33	200W_-8°C	200W	-8.1	0.6	8.64E-11	2.10E-04	550

This comparison has been limited to dehydration experiments with an applied power of 100 W, 150 W and 200 W. Although there are not notorious differences between the three power levels, it can be appreciated how the process time is reduced when the applied power is increased. The required time to reduce the weight of the apple samples up to 80% of the initial weight (a moisture content of 1.23 kg_{water}/kg_{dry matter}) when applying 100 W was 10.5±1.1 h. Increasing the applied power was reflected in a reduction of the process time: 9.7±0.4 h for an electric supply of 150 W; and 9.2±0.5 h for an electric supply of 200 W. Hence, even for high power levels, the supplied power has certain influence in the dehydration kinetics, as it can be observed in Table 6.7.

The representation of the drying kinetics under the three operational conditions analyzed (Fig. 6.16) permits the comparison between the experimental (dots) and modelled (lines) curves at each case. Thus, it can be observed that the modelled drying kinetics fitted adequately the experimental results and both, experimental and calculated curves followed the same trend.

Table 6.7.- Dehydration coefficients by modelling experimental AFD kinetics at -8 °C.

Ultrasonic power applied					
	100 W	150 W	$\Delta\%$	200 W	$\Delta\%$
D_e (10^{-11} m ² /s)	6.52±1.5	8.21±2.4	25.9	8.64±5.7	32.5
k (10^{-4} kg _{water} /m ² s)	1.83±0.2	2.07±0.2	13.1	2.1±0.2	14.8
Drying time (h)	10.5±1.1	9.7±0.4	7.6	9.2±0.5	12.4
Correlation coefficient (%)	99.8	99.9		99.9	
Explained variance (%)	99.8	99.9		99.9	
Mean relative error (%)	13.9	4.5		8.9

Fig. 6.16.- Experimental and calculated moisture evolution during drying apple slices (-8 °C).

The accuracy of the model fitting was quantified by three parameters: the correlation coefficient, the explained variance and the relative mean error (see Table 6.7). The maximum relative mean error has been obtained for experiments with an applied power of 100 W (13.9%), because the variability obtained in the experiments considered in this case. The experiments under other power levels (150 W and 200 W) show lower relative mean error. On the other hand, the correlation coefficient and the explained variance in the three cases are always higher than 99.8%.

The values identified of D_e and k confirms that, even for high power supplies up to 200 W, the amplitude of electric power supplied has influence in the enhancement of AFD processes. Nevertheless, the improvements obtained for very high power may not justify an electric supply of 200 W. Thus, compared to 100 W experiments, the D_e increased 26% in 150 W experiments and 32 % in 200 W ones. Similar influence of ultrasound application was observed for the k parameter. Thus, the value identified in 150 W experiments was 13.1 % higher than the identified in

experiments carried out with 100 W ultrasound application while 14.8 % in the case of 200 W experiments.

6.4.2- Influence of the dehydration temperature in drying kinetics

Another interesting analysis of the lyophilization experiments carried out over apple samples is the effect of the drying temperature, or the temperature existent inside the dehydration cabinet. For this analysis, two groups of experiments are considered, experiments carried out with no ultrasounds and experiments carried out with maximum power (200 W).

6.4.2.1- Experiments without ultrasounds

The analysis of the influence of the environmental temperature in drying kinetics has been carried out considering the sets of experiments done without the application of ultrasounds (0 W). The experiments considered are those indicated in Table 6.8.

Table 6.8.- Data for the analysis of influence of temperature without ultrasounds.

Tests	Code	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m ² /s)	Mass transfer k (kg _{water} /m ² s)	Duration (min)
1, 2, 3, 4	NoUS_-3°C	0W	-3.0	2.9	7.77E-11	2.21E-04	533
5, 6, 7, 8	NoUS_-13°C	0W	-13.2	2.9	2.42E-11	8.69E-05	1450
9, 10, 11, 12	NoUS_-17°C	0W	-17.2	3.9	1.35E-11	1.05E-04	2300

According to Table 6.8, the temperature at which the experiments are carried out is crucial in the drying kinetics. The higher the temperature, the shorter the process is. Thus, the samples dried without ultrasound at about -3 °C needed only 8.9±0.9 h to reach an 80% initial weight loss (a moisture content of 1.23 kg_{water}/kg_{dry matter}), while experiments carried out at lower temperatures took much longer to reach the desired weight. For example the drying time needed to reach an 80% initial weight loss for -13 °C experiments was 24.1±1.4 h, almost three times the time required at -3 °C, while 38.3±4.1 h for -17 °C experiments, that is more than four times (see Table 6.9).

Table 6.9.- Dehydration coefficients by modelling experimental AFD kinetics without ultrasounds.

	Temperature				
	-3°C	-13°C	Δ%	-17°C	Δ%
D_e (10 ⁻¹¹ m ² /s)	7.77±2.3	2.42±0.4	31.1	1.18±1.9	15.2
k (10 ⁻⁴ kg _{water} /m ² s)	2.21±0.2	0.87±0.06	39.4	0.72±0.1	32.6
Drying time (h)	8.9±0.9	24.1±1.4	170.8	38.3±4.1	330.3
Correlation coefficient. (%)	99.8	99.4		99.3	
Explained variance (%)	99.8	99.3		99.3	
Mean relative error. (%)	8.5	10.9		12.6	

The values of the effective diffusivity coefficient (D_e) and mass transfer coefficient (k) have been obtained by modelling the experimental dehydration kinetics of apple with different environmental temperatures (-3 °C, -13 °C and -17 °C). In Table 6.9, $\Delta\%$ represents the difference, in percentage, of the value of each parameter with the experiments at the highest temperature (-4 °C). The values of D_e and k are lower when the temperature is lower, so the time required to reach a final weight of 80% is higher.

The representation of the drying kinetics under the three operational conditions analyzed (Fig. 6.17) permits the comparison between the experimental (dots) and modelled (lines) curves at each case. The accuracy of the model fitting is quantified by the correlation coefficient, the explained variance and the relative mean error presented in Table 6.9. These parameters indicate good values of correlation and explained variance, but the mean relative error is about 10% in all cases, due to the variability obtained in the experiments, mainly at -17 °C.

Fig. 6.17.- Experimental and calculated moisture evolution during drying apple slices (No US).

The values identified of D_e and k confirms the high influence of the lyophilization temperature, mainly in the case of the effective diffusivity coefficient (D_e). In this case, compared to -3 °C experiments, the D_e decreased almost 69% in -13 °C experiments and almost 85% in -17 °C ones. The values of the mass transfer coefficient (k) presented also important decreases for lower experiment temperatures, even if these decreases are not as extreme as the case of D_e . Again, compared to -3 °C experiments, the value of k decreased more than 60% in -13 °C experiments and more than 67% in -17 °C ones.

This analysis proves the crucial importance of the temperature at which the experiments are conducted. The analysis of the influence of drying temperature in dehydration experiments assisted by power ultrasound is presented in the following section.

6.4.2.2- Experiments with power ultrasounds (200 W)

The following analysis corresponds to the influence of the environmental temperature in drying kinetics when the process is assisted by power ultrasound. In this case, the electric power applied to the APU transducer is 200 W. The experiments considered are those indicated in Table 6.10.

Table 6.10.- Data for the analysis of influence of temperature in experiments with an electric supply of 200W.

Tests	Code	Electric power (W)	Temperature (°C)	Relative humidity (%)	Effective diffusivity D_e (m ² /s)	Mass transfer k (kg _{water} /m ² s)	Duration (min)
30, 31	200W_-4°C	200W	-3.8	0.5	1.23E-10	2.64E-04	417
32, 33	200W_-8°C	200W	-8.1	0.6	8.64E-11	2.10E-04	550
34, 35, 36	200W_-11°C	200W	-11.4	3.5	4.31E-11	2.29E-04	800

According to Table 6.10, the environmental temperature determines the processing time, although the use of power ultrasounds in the process reduces the influence of the temperature. In this case, the samples dried at about -4 °C needed only 6.9±0.2 h to reach an 80% initial weight loss (a moisture content of 1.23 kg_{water}/kg_{dry matter}), while experiments carried out at lower temperatures took much longer to reach the desired weight. For example the drying time needed to reach an 80% initial weight loss for -8 °C experiments was 9.2±0.5 h, while 13.3±0.8 h for -11 °C experiments, that is less than double time than the required at -4 °C.

Table 6.11.- Dehydration coefficients (D_e and k) by modelling experimental AFD kinetics with ultrasounds (200W).

	Temperature				
	-4°C	-8°C	Δ%	-11°C	Δ%
D_e (10 ⁻¹¹ m ² /s)	16.1±5.1	8.9±6.2	55.3	3.8±0.6	23.6
k (10 ⁻⁴ kg _{water} /m ² s)	2.47±0.1	1.99±0.2	80.6	1.62±0.1	65.6
Drying time (h)	6.9±0.2	9.2±0.5	33.3	13.3±0.8	92.8
Correlation coefficient (%)	99.9	99.9		99.9	
Explained variance (%)	99.8	99.9		99.9	
Mean relative error (%)	4.1	1.8		3.4	

The values of the effective diffusivity coefficient (D_e) and mass transfer coefficient (k) have been obtained by modelling the experimental dehydration kinetics of apple with different environmental temperatures (-4 °C, -8 °C and -11 °C) and an electric supply to the APU transducer of 200 W. In Table 6.11, Δ% represents the difference, in percentage, of the value of each parameter with the experiments at the highest temperature (-4 °C). The values of D_e and k are lower when the temperature is lower, so the time required to reach a final weight of 80% is higher.

The representation of the drying kinetics under the three operational conditions analyzed (Fig. 6.18) permits the comparison between the experimental (dots) and modelled (lines) curves at each case. The accuracy of the model fitting is quantified by the correlation coefficient, the explained

variance and the relative mean error presented in Table 6.11. According to these parameters, a good fitting between the experimental and numerical determinations has been obtained, with a maximum error of 4.1 %.

The values identified of D_e and k confirms the influence of the lyophilization temperature, mainly in the case of the effective diffusivity coefficient (D_e). In this case, compared to $-4\text{ }^{\circ}\text{C}$ experiments, the D_e decreased almost 45% in $-8\text{ }^{\circ}\text{C}$ experiments and almost 76% in $-11\text{ }^{\circ}\text{C}$ ones. The values of the mass transfer coefficient (k) presented also decreases for lower experiment temperatures, even if these decreases are not as extreme as the case of D_e . Again, compared to $-4\text{ }^{\circ}\text{C}$ experiments, the value of k decreased almost 20% in $-8\text{ }^{\circ}\text{C}$ experiments and almost 35% in $-11\text{ }^{\circ}\text{C}$ ones.

It has been proved that the environmental temperature is important in the kinetics of airborne freeze drying. The lower the chamber temperature, the higher the time required in the process. The influence of the environmental temperature is important in processes without ultrasounds and, to a lesser extent, in processes assisted by power ultrasounds up to an electric supply of 200 W.

Fig. 6.18.- Experimental and calculated moisture evolution during drying apple slices (200W).

6.5- Conclusions.

This last chapter is focused on the practical application of one of the systems developed for mass transfer processes, more specifically, for lyophilization at atmospheric pressure of food samples (also airborne freeze drying, or AFD). The APU transducer used for this purpose has a stepped-grooved circular radiator.

The APU transducer is placed inside a drying chamber, where the environmental conditions are kept in the desired values of relative humidity (as close to zero as possible) and temperature (always below the freezing point). The APU transducer has been placed with the stepped profile oriented to the food samples, and separated about 20 cm. The acoustic field generated by the APU

transducer corresponds to a coherent field in free field, and inside the chamber due to the little influence of the reflected waves inside the chamber.

The AFD experiments have been carried out over apple slices with a thickness of 3 mm, and with different temperatures inside the chamber (between -3 °C and -17 °C) and different electric power supply to the APU transducer (between 0 W and 200 W). An initial moisture content of the apple samples has been determined experimentally, to delimit the end of the experiment when the weight of the samples decays 80% of the initial.

A total of 36 experiments have been done, combining different temperatures and supplied powers. An acceleration of the dehydration kinetics has been obtained with the use of power ultrasounds, being greater with higher supplied power. Nevertheless, only the fact of applying ultrasound implies an important enhancement of the process, being less important the amplitude of the electric power.

On the other hand, the temperature inside the cabinet is crucial in the dehydration kinetics. Experiments at -3 °C are much faster than experiments at -12 °C or -17 °C. It is necessary to clear that the application of acoustic waves provokes a warming up of the propagating medium and, of course, of the food samples. In experiments at -4 °C assisted by power ultrasounds, the temperature in the samples may be over the freezing point.

The ultrasonically assisted AFD can be an interesting alternative to an expensive and high-demand energy process such as vacuum freeze-drying. What is now required is to increase efforts directed toward scaling-up APU application taking into consideration issues such as drying chamber configuration which will improve the ultrasonic efficiency as well as procedures for the mass production of ultrasonic transducers.

This has been the first time that an APUT with circular plate has been applied in AFD experiments assisted by power ultrasound. This led to a number of contributions as follow:

- **Journal paper.** 2019. R. R. Andrés, E. Riera, et al., "Airborne power ultrasound for drying process intensification at low temperatures: Use of a stepped-grooved plate transducer," *Drying Technology*, pp. 1-14.
- **Conference paper.** 2019. R. R. Andrés, E. Riera, et al., "State-of-the-art in the application of airborne power ultrasonic technologies in atmospheric freeze drying processes," *Proceedings of Meetings on Acoustics*, vol. 38, p. 032005.
- **Conference paper.** 2019. R. R. Andrés, A. Pinto, J. A. Cárcel, and E. Riera, "Airborne power ultrasonic transducers with stepped circular radiator for lyophilization at atmospheric pressure," *Proceedings of Meetings on Acoustics*, vol. 38, p. 030011.
- **Congress presentation.** 2018. R. R. Andrés, J. A. Cárcel, and E. Riera, "New ultrasonically assisted drier for atmospheric freeze-drying processes," presented at the XI Congreso Iberoamericano de Acústica FIA 2018, Cádiz (Spain).
- **Congress presentation.** 2019. R. R. Andrés and E. Riera, "Optimization of the acoustic pressure distribution inside a freeze drying chamber," presented at the COMSOL Conference, Cambridge.

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7.- CONCLUSIONS

The use of power ultrasounds as an aid in food dehydration processes has been proved to be efficient in terms of acceleration of the process and quality of the final product at least in dehydration at high temperatures. These advantages have also been proved to work in dehydration experiments under different temperature and air flow conditions.

An airborne power ultrasonic transducer is the tool that generates the high-intensity ultrasonic field capable of activating the desired mechanisms, which facilitates the transport of the water placed inside the food samples along the solid matrix and then to the surrounding environment. These mechanisms are the following:

- A microsp sponge effect originated by the vibration of the solid matrix due to the incident ultrasonic energy. The vibration of the food molecules allow an easier separation of the water content and an easier displacement along the microchannels existent in the food samples to its external boundaries.
- An acoustic streaming in the boundary layer, which reduces the external resistance for the water to evaporate/sublimate into the surrounding medium.

In the case of freeze drying, of lyophilization at atmospheric pressure, a successful application of ultrasound was only reached with an airborne power ultrasonic transducer with a cylindrical radiator. This transducer is capable of generating a high-intensity ultrasonic field in the cavity. This cavity has a total volume of 2.43 l (0,00243 m³), implying that the amount of product to be processed is very small for an industrial upscaling of this technology. Nevertheless, it was proved that this technology may work efficiently under these conditions.

The objective of this work was to design, characterize and test new ultrasonic systems capable of enhancing lyophilization at atmospheric pressure processes with a bigger amount of samples in order to get closer to an efficient industrial upscaling of this technology.

7.1- Ultrasonic systems for lyophilization at atmospheric pressure

The main condition to take into account in the design of ultrasonic systems for food dehydration is that they should generate a coherent ultrasonic field, covering a wide volume. Two systems have been designed and characterized:

- An airborne power ultrasonic transducer with a stepped-grooved circular radiator that vibrates in an operational mode with seven nodal circles (7NC) at a frequency around 26 kHz.
- An airborne power ultrasonic transducer with a flat rectangular radiator and a reflectors system that vibrates in an operational mode with twelve nodal lines (12NL) at a frequency around 21 kHz.

7.1.1- APU transducer with stepped-grooved circular radiator

This first system was designed from previous similar transducers, but scaling the radiator, increasing its surface and setting its operational mode to a higher mode, in this case with 7NC.

The numerical design, using FEM, estimated a good ultrasonic system, capable of working in a high power regime; obtaining high values of displacement with an appropriate distribution along the plate for the generation of a coherent ultrasonic field. The numerical characterization also predicted that no modal interaction between close modes is expected when operating under a high power regime.

On the other hand, the expected ultrasonic field, also analyzed numerically using FEM, presented a coherent distribution similar but not equal to the distribution of the ultrasonic field generated by a piston.

The following step is the manufacturing of the transducer and its experimental characterization. This characterization includes several types of experiments:

- **Low power characterization.** Carried out using the impedance analyzer, the low power characterization gave as a result an ultrasonic system with a high quality factor ($Q = 4613$) and a narrow bandwidth ($BW = 5.6$ Hz). The operational frequency with 7NC was found at 25835 Hz, and the efficiency of the system was 70.3 %.
- **Stability tests.** Carried out by tracking the system at its operational mode, even if the frequency was moving. This test presented a stable behavior of the transducer when operating under a high power regime (up to 200 W), without showing any symptoms of saturation after long periods of continuous work.
- **Nonlinear dynamic characterization.** Carried out with the characterization system based on Labview® (see Fig. G. 2 in Annex G). The first set of experiments, based on the relationship of several magnitudes with the APU transducer working under continuous wave operation at its operational mode, shows a normal behavior of the system, without experiencing major issues due to excessive heating of the components, and a normal relationship between the electrical and mechanical variables. On the other hand, 2D sweeps around resonance show highly linear responses of the system, showing symmetry near overlap in the forward and backward sweep responses and no evidence of a bending backbone curve that would signify a softening or hardening nonlinearity. Moreover, no hysteretic responses have been found, meaning that this is a very stable system.
- **Experimental modal analysis.** Carried out with a 3D laser vibrometer, this analysis confirms that no modal coupling should be expected in the plate radiator transducer in operation since the frequency separation of the modes (more than 400 Hz) is sufficient to ensure no modal interaction.

So, the experimental characterization of the APU transducer gave as a result a very good ultrasonic system, with a high quality factor and efficiency, and without any remarkable nonlinear effect when operating under high power regime.

Regarding the ultrasonic field generated by the system, it has been characterized experimentally in a semianechoic chamber, by means of a measurements campaign where the

pressure distribution along the axis and several planes perpendicular and parallel to the radiator has been obtained. This determination has proved that the system is capable of generating an ultrasonic field similar to the field generated by a piston, with a distribution of maximum and minimum values in the near field and an energy concentration in the separation between the Fresnel and Fraunhofer zones. In the far field, the spherical propagation provokes a continuous decrease of the pressure amplitude for volume unit..

7.1.2- APU transducer with flat rectangular radiator and a reflectors system

The second system, with a rectangular radiator, was designed with a flat surface and a reflectors system for two reasons:

- Rectangular plates with stepped profile did not show a good behavior when applying high power. So, the surface of the radiator is flat.
- The reflectors system, where the steps are applied, allow an in-phase radiation, using the ultrasonic energy generated by both sides of the radiator.
- The radiator is made of duraluminium 7075 because of the lower cost of the material.

The transducer was designed to vibrate in an operational mode with twelve nodal lines (12|0) at a frequency around 21 kHz. The addition of the reflectors system has an effect in the acoustic field generated by the transducer, but not in the dynamic behavior of the system, which depends only on its active part.

The numerical characterization of this APU transducer presents a good ultrasonic system, capable of working in a high power regime, and obtaining high values of displacement, even if the mechanical stress suffered by the bolt and the plate can be high.

On the other hand, the characterization of the ultrasonic field has been done by comparing the pressure distribution field generated by the APU transducer with flat rectangular radiator without and with reflectors (see Chapter 3.5.3). It can be perceived that the system with reflectors doubles the radiating surface, and that there are higher pressure amplitudes in the free field. This occurs by constructive interferences that happen after putting in phase the acoustic waves with the reflectors.

The following step is the manufacturing of the transducer and its experimental characterization. This characterization includes several types of experiments:

- **Low power characterization.** The low power characterization gave as a result an ultrasonic system with a very high quality factor ($Q = 13268$) and a narrow bandwidth ($BW = 1.6$ Hz). The operational frequency with 12NL was found at 21097 Hz, and the efficiency of the system was 80.0 %.
- **Stability tests.** This test presented a stable behavior of the transducer when operating under a high power regime (up to 400 W), without showing any symptoms of saturation after long periods of continuous work.
- **Nonlinear dynamic characterization.** The set of experiments based on the relationship of several magnitudes with the APU transducer working continuously at its operational mode, shows a normal behavior of the system, without experiencing major issues due to excessive heating of the components, and a normal relationship between the electrical and mechanical

variables. On the other hand, 2D sweeps around resonance show highly linear responses of the system, exhibiting symmetry near overlap in the forward and backward sweep responses and no evidence of a bending backbone curve that would signify a softening or hardening nonlinearity. Moreover, no hysteretic responses have been found, meaning that this is a very stable system. Overall, the nonlinear characterization has shown a very stable transducer exhibiting no adverse influences of temperature, modal interactions or nonlinear responses.

- **Experimental modal analysis.** This analysis confirms that no modal coupling should be expected in the plate radiator transducer in operation since the frequency separation of the modes is sufficient to ensure no modal interaction.

So, the experimental characterization of the APU transducer gave as a result a very good ultrasonic system, with a high quality factor and efficiency, and without any remarkable nonlinear effect when operating under high power regime.

Finally, the experimental study of the ultrasonic field generated by the system without and with reflectors was carried out in two different experiments:

- The pressure distribution has been measured in a semianechoic chamber for both configurations. The results obtained after this determination reflect the improvements obtained when using the reflectors, confirming therefore the expectations obtained in the numerical analysis (see Chapter 5.2.5.1).
- The directivity pattern of the emission of both systems was determined experimentally in an anechoic chamber by measuring the pressure distribution at 7.8 m in a sector of 180°. According to this, the ultrasonic system with reflectors shows a higher directivity than conventional APUTs, concentrating most of the acoustic energy in the axial direction, while the system without reflectors radiates the acoustic energy in two main lobes that form 10° angles with the axis. (see Chapter 5.2.5.2).

7.2- Effect of the shape of the horn in APUT's with rectangular radiator

The transducers used for high power applications require a high efficiency to provoke the desired effects in the media. The electric power supplied to the system must be transformed into mechanical vibrations in the thickness mode of the Langevin transducer, minimizing the losses, and this vibration must propagate to the radiator, obtaining maximum values of vibration displacement and velocity.

The efficiency of the previous designs is quite good. Nevertheless, the shape of the union area between the mechanical amplifier and the rectangular radiator has been studied to find ways to improve this efficiency, taking into account that the rectangular shape of the radiator is not axisymmetric, and that the operational mode of these plates has always a number of parallel nodal lines.

A numerical and experimental analysis has been carried out with an airborne power ultrasonic transducer designed for this purpose, where adapters with different shapes could be placed between the mechanical amplifier and the rectangular radiator.

The numerical study allowed an initial selection of five adapters with different shapes and dimensions, whose effects in the behavior of the transducer could be analyzed experimentally. These adapters are the following:

- Adapter 1.- Adapter with a circular shape. External radius 10.5 mm.
- Adapter 2.- Adapter with a short-rounded shape. Rectangle with sides 18 mm x 14 mm and rounded ends with radius 9 mm.
- Adapter 3.- Adapter with a long-rounded shape. Rectangle with sides 18 mm x 26 mm and rounded ends with radius 9 mm.
- Adapter 4.- Adapter with a squared shape. Side of 25 mm.
- Adapter 5.- Adapter with a rectangular shape. Dimensions 27 mm x 21 mm.

The experimental characterization of the ultrasonic system with the five adapters was carried out under different settings, including low power characterization in the impedance analyzer, stability tests and dynamic tests under a high-power regime. The results obtained can be observed in Table 5.8, where the circular and the short rounded adapters show the most efficient behavior when applying low electric supply (impedance analysis experiments), and in terms of power capacity. The configurations studied present similar nonlinear behavior, with the appearance of a parametric vibration when applying an electric supply over 30 V in frequency sweeps.

So, according to the results obtained from the experimental analysis of all the configurations, the short-rounded shape seems to be promising in terms of efficiency of the new system, even if in the present analysis, the transducer with the traditional circular shape shows a good behavior.

7.3- Effect of the application of power ultrasounds in food dehydration

The last objective of this work is to evaluate the effect of the application of these new systems in mass transfer processes, specifically in lyophilization at atmospheric pressure of food samples.

This evaluation has been carried out with the APU transducer with stepped-grooved circular radiator acting over 3 mm-thick apple samples.

The APU transducer was placed inside a drying chamber, where the environmental conditions are kept in the desired values of relative humidity (as close to zero as possible) and temperature (between -3 °C and -17 °C). The electric power supply to the APU transducer was chosen between 0 W and 200 W.

A total of 36 experiments have been done, combining different temperatures and supplied powers. An acceleration of the dehydration kinetics has been obtained with the use of power ultrasounds. The time required to reduce the weight samples 80% from the initial decreases by increasing the supplied power. Nevertheless, this evolution is not linear, but only the fact of applying ultrasound implies an important enhancement of the process, being less important the amplitude of the electric power. On the other hand, the temperature inside the cabinet is crucial in the dehydration kinetics. Experiments at -3 °C take much shorter than experiments at -12 °C or -17 °C to reach a weight reduction of 80% of the initial.

The enhancement of this process using an APU transducer with stepped circular radiator is not as notorious as the enhancement obtained with a cylindrical radiator because the acoustic energy generated by the circular plate is not confined in a small volume, like in the case of cylinders. Nevertheless, this new system may be adapted to an industrial scale easier than systems with cylindrical radiators.

7.4- Final conclusion and future work

This work represents the first time that AFD processes assisted by power ultrasound have been carried out using an airborne power ultrasonic transducer with a stepped-grooved circular radiator.

This work has supposed an important contribution in the field of power ultrasonics and food processing, reflected in the publication of several journal papers, collaboration in book chapters, conference papers and presentations in national and international congresses (see Annex H).

Nevertheless, the upscaling of this technology to an industrial scale needs some issues to solve previously. These issues are related to the drying chamber configuration which will improve the ultrasonic efficiency as well as procedures for the mass production of ultrasonic transducers.

Hence, to reach the final goal, some works have to be carried out previously:

- **Improve the efficiency of the ultrasonic systems.** The analysis of the effect of the shapes of the contact area between the mechanical amplifier and the radiator, as a function of the operational mode of the transducer, gave initial conclusions. The use of a short-rounded shape in the rectangular radiator may improve the efficiency of the system. This would be an initial step to explore new shapes like oval shapes or improve the machining of the components by avoiding removable adapters or fixing the adapter and the radiator to minimize losses in that area.
- **Complete the freeze-drying experiments with the APUT with stepped-grooved circular plate.** Other types of samples can be considered, like fruits and vegetables with different properties in terms of porosity. Also, an extension of the experimental study can be carried out by distributing higher amount of samples along the whole volume affected by the ultrasonic field generated by the system, providing new characterization variables like the total weight of food processed at the same time. This extension would permit a more favorable comparison between this system and the APUT with cylindrical radiator because the amount of product processed would be much higher.
- **Evaluate the APU transducer with flat rectangular radiator and reflectors in freeze drying processes.** This would be the first work to carry out after this research. The ultrasonic system presented in this document has not been tested so far, so it is important to check if the efficiency of such system in food dehydration experiments increases the efficiency of previous systems in terms of acceleration of the process and amount of food processed at the same time.
- **Scale the ultrasonic systems.** The introduction of this technology in the actual food industry will require a high amount of product to be processed, so, the ultrasonic systems should be capable of doing it. It is necessary these systems to be bigger and to act over higher volumes. This is a matter of research numerically and experimentally in the future.

As a conclusion, next works should be focused on an extended testing of the current transducers and on its upscaling and optimization to have ultrasonic systems capable of processing higher volumes with a good efficiency.

ANNEX A.- EFFECTS OF NONLINEAR PHENOMENA CREATED BY POWER ULTRASOUND

Wave distortion, saturation, radiation force, acoustic streaming, instability at the interfaces and structural diffusion in gases, cavitation in liquids and the formation of dislocations in solids are the most relevant nonlinear mechanisms whose intensity depends on the amplitude of vibrations and are known as nonlinear effects [2, 162]. These mechanisms are described in more detail in the following paragraphs:

Wave distortion. If a high-intensity, sinusoidal wave propagates in a fluid media its shape changes with distance because the propagating velocity depends of the local particle velocity. That means that it varies from point to point on the waveform so that the regions that correspond to compression, travel faster than the rarefaction regions. As a result, the sinusoidal wave is transformed into a shock wave, before the wave becomes sinusoidal again due to the viscosity and heat conductivity losses in the propagating medium [4]. Therefore, the propagation path of an original sinusoidal wave of finite amplitude in a thermoviscous fluid may be divided into three regions (Fig. A. 1). In the first region (I), which extends up to the shock formation, the nonlinear effects dominate. The second region (II) corresponds to the formation and propagation of a relatively stable sawtooth wave. Finally, in the third region (III), which is known as old age region, the decay rates due to nonlinear effects are balanced by ordinary absorption, and the wave becomes sinusoidal again. The distortion of the waveform is associated to the presence of high frequency harmonics in the wave [163, 164].

Fig. A. 1.- Nonlinear propagation path of a sinusoidal wave of finite amplitude in air at different distances from the source.

Acoustic saturation. The attenuation of high-intensity waves is not constant; it depends on the distance from the source and increases with the wave amplitude. This phenomenon is a consequence of the wave distortion and limits the amount of energy that can be transmitted at a certain distance from the source. In fact, the wave distortion at a fixed point in the radiation field increases when the amplitude of vibration of the source increases. The wave energy is transferred to higher-order harmonics, which, since the absorption increases with the square of the frequency, are absorbed quickly causing an excess of attenuation of the wave. This behavior will determine that above a certain value, any increase of the wave amplitude generated at the source will be compensated by its decay in the considered point. Therefore, there is a limiting magnitude of the wave amplitude that can be reached at a fixed distance from the source in a given medium [4]. For instance, in air at a frequency of 20 kHz the maximum sound pressure level which can be transmitted to a distance of 5.7 m away from the source is only 121 dB (Fig. A. 2). Therefore, the great significance of the limiting value due to acoustic saturation in practical applications of high-power ultrasound should be emphasized [6, 163].

Fig. A. 2.- Effect of acoustic saturation of an ultrasonic wave in air at 5.7 m from the source.

Radiation force. When a high-intensity ultrasonic wave propagates in a medium in the presence of obstacles and interphases, continuous steady radiation forces that act on said obstacles and interphases are produced. The presence of the radiation pressure is linked to any wave process and has its origin in the change of moment that the wave experiences when acting on an obstacle or interphase. These forces are intense for power ultrasonic waves giving rise to drag and interaction. The calculation of the radiation pressure yields to different results depending on the conditions of the obstacle and the acoustic field. Thus, the radiation pressure exerted on a plane target by an ultrasonic beam confined by rigid walls preventing inflow of fluid into the beam is known as the Rayleigh radiation pressure. Instead, if the target is placed in the path of an unbounded ultrasonic beam, the time averaged force per unit area acting on it is called the Langevin radiation pressure. The action of radiation forces on different obstacles or interphases in multiphase media represents an important mechanism at the basis of many effects produced by high-intensity ultrasonic waves. Generally, the acoustic radiation force generated by a plane wave

exerted on the obstacle is evaluated by integrating the acoustic radiation pressure over its time-varying surface. The magnitude of the radiation force (R_F) at any given location can be calculated as indicated in Eq. A. 1.

$$|R_F| = \frac{2\alpha I}{c_0} \quad \text{Eq. A. 1}$$

For instance, solid or liquid particles suspended in a gas (aerosol) under the action of an acoustic field execute a number of motions that are governed by different acoustic effects. Thus, particles take some part in the vibrations of the fluid and follow translational motions mainly due to the radiation force, among others. The radiation force exerted on a stationary spherical particle of arbitrary density, of which the radius a is smaller than the wavelength, $ka \ll 1$, where k is the wave number, was evaluated by King [165] for a traveling wave as shown in Eq. A. 2 and for a standing wave is presented in Eq. A. 3.

$$|R_F| = \frac{11\pi}{9} \left(\frac{\omega}{c_0^2} \right)^4 a^6 (1 - H^2) E \quad \text{Eq. A. 2}$$

$$|R_F| = \frac{8\pi}{3} \left(\frac{\omega}{c_0} \right) a^3 (1 - H^2) E \sin(2kx) \quad \text{Eq. A. 3}$$

$$H = \frac{U_p}{U_g} \quad \text{Eq. A. 4}$$

Where H is the entrainment factor, U_p is the amplitude of the particle velocity, U_g the amplitude of the gas velocity and E is the sound energy density (see Eq.1. 10) [15]. The radiation force is in the direction of the wave propagation for the traveling wave.

Acoustic radiation forces on compressible particles such as bubbles are known as Bjerknes forces, and are generated through a different mechanism, which does not require sound absorption or reflection.

Acoustic streaming. Because of the ultrasonic absorption processes that occur during the propagation of high-intensity waves in fluids, the generated radiation forces induce movements to the irradiated fluid. This fluid motion can assist in improving the transfer of matter and heat. Acoustic streaming is a nonlinear acoustic effect in which steady fluid flows are induced by finite-amplitude acoustic waves. In a high-intensity ultrasonic field steady flows are produced both in the free ultrasonic beam and near obstacles. In the latter case, the boundary layer has a significant influence in the development of the steady flows. Outside the boundary layer, in a travelling wave, the fluid flows away from the source at the center of the ultrasonic beam and in the opposite direction at the periphery (Fig. A. 3 and Fig. A. 4) [166]. In a standing wave, a series of closed vortices are established between nodes and antinodes. Acoustic streaming seems to be mainly induced by radiation forces set up by absorption of the ultrasonic waves in the medium. However, other mechanisms, such as diffraction and nonlinearities of the acoustic field, may also contribute to this effect.

Fig. A. 3.- Acoustic streaming generated by a travelling wave over a cylindrical container.

Fig. A. 4.- Acoustic streaming set up in a sound field: a) travelling wave; b) standing wave.

Instabilities at the interfaces. High-intensity ultrasound produces pressure variations in the solid-gas and liquid-gas interfaces that may influence the rate of evaporation/sublimation (as a function of temperature) of the solvent molecules retained in the solid matrix of a product. This process is particularly relevant in food dehydration as well as in the removal of organic solvent in the chemical and pharmaceutical industries. During the negative phase of the pressure cycle, the pressure of the solvent at the solid surface decreases, enhancing its transport to the surrounding fluid. The high-intensity ultrasonic energy also causes oscillating velocities and microstreaming at the interface that may contribute to a decrease in the thickness of the diffusion boundary layer. This reduces the external resistance to the mass transfer, thereby increasing the convective transport. The effects of ultrasound at the interfaces can also influence the internal resistance to mass transport, which will affect the intercellular spaces inside the matrix. These phenomena will be more intense in those materials with a wide network of intercellular spaces [4].

Structural diffusion. When the ultrasonic energy propagates through the solid, semi-solid or liquid matrix, it causes rapid series of alternative contractions and expansions. This process could be similar to what happens when a sponge is squeezed and relaxed, and so it is known as microsp sponge effect [29, 142, 155]. These alternate stresses facilitate the internal movement and

elimination of the solvents like moisture or ethanol through the microscopic channels created by the propagation of the wave, increasing the diffusion coefficients [67].

Cavitation in liquids. This is the major mechanical effect of PU waves in liquids. Currently cavitation can be defined as the formation (nucleation), pulsation (cavity growth), and/or implosive collapse of tiny discontinuities, cavities or microbubbles in liquids. Cavities/bubbles appear as a result of the tensile stress produced by an ultrasonic wave in the rarefaction phase. There are two types of cavitation: stable and transient (or inertial) cavitation. Stable cavities produced at moderate ultrasonic intensities, are bubbles oscillating non-linearly around their equilibrium size, which may continue oscillating for many cycles of the ultrasonic pressure and grow by trapping the dissolved gas in the liquid [167-170]. On the contrary, transient cavities usually exists for less than one cycle (created from existing gas nuclei within the fluid) and are generated by very high-intensity ultrasonic fields. The acoustic resonance frequency of a single air bubble in water without viscous attenuation effects is given by Eq. A. 5, where R_r is resonance radius of the bubble, p_0 is the ambient liquid pressure and ρ_l liquid density. Thus, in the case of a gas bubble in water in ambient conditions, Eq. A. 5 reduces to Eq. A. 6.

$$f_r = \frac{1}{2\pi R_r} \sqrt{\frac{3p_0}{\rho_l}} \quad \text{Eq. A. 5}$$

$$f_r R_r = 0.328 \text{ kHz cm} \quad \text{Eq. A. 6}$$

For $f_r=20$ kHz the resonance radius is 150 μm , while for $f_r=1$ MHz, the resonance size drops up to 3.3 μm . If the amplitude of the ultrasound wave is great enough for the liquid, during the negative half-cycle of oscillation, a cavity will rapidly expand to many times their original size. Then, during the compression half-cycle of oscillation, the cavity collapse or implode violently. This collapse leads to the formation of jets and shock waves, as well as the most extreme effects of transient cavitation linked to the high temperatures (~ 5000 K) and pressures (~ 1000 atm) produced during bubble collapse. The high pressures may cause erosion, dispersion, and mechanical rupture, whereas the high temperatures are responsible for sonochemical and sonoluminescence effects [170, 171]. The intensity of cavitation and its effects depend on the characteristics of the liquid medium, such as viscosity and process variables, such as ultrasonic intensity, ultrasonic frequency or pressure.

In addition, PU induces a series of mechanisms such as heat, agitation, friction, diffusion, mechanical rupture and chemical effects (in liquid media) that are generally used to enhance different processes that are dependent on the treated medium. In solids, machining, cutting, drilling, welding, metal forming and powder intensification are good examples among others, together with cleaning, washing, emulsification, atomization of liquids, defoaming, degassing, drying, ultrasonic agglomeration, separation solid-liquid, acceleration of chemical reactions, etc., in fluids and multiphase media. In this chapter, we will focus our attention on the understanding and application of power ultrasound (PU) to intensify some processes at laboratory and semi-industrial scale such as aerosol particle agglomeration, defoaming, hot-air convective drying, and supercritical fluid extraction with dense gases [4]

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ANNEX B.- ELECTROMECHANICAL ANALOGIES

The term transduction implies the conversion of energy of a specific type to energy of a different one. The ultrasonic generation by an APUT is based on a double transduction; the initial electric energy is converted into mechanical energy, which suffers another conversion into acoustic energy.

For example, audio devices are transducers, both emitters and receivers. A loudspeaker is based, as well as ultrasonic transducers, in a double transduction. The electric signal transports the information and provokes an excitation to the membrane, which vibrates in an analogous way and generates an acoustic field that carries the same information than the electric signal, in a different form of energy.

Pressure microphones are also transducers based on a double transduction. Here the information is transported by the acoustic wave, which provokes a movement of a condenser's membrane that originates analogous voltage variations with the same information.

Focusing on the electrical-mechanical transduction, it must be done by materials that react mechanically to an electric input. The two dominant transduction techniques are piezoelectricity and magnetostriction, both discovered in the 19th Century [1]. Considering that most of the power transducers currently used are piezoelectric, we will focus on this transduction technique in the following sections.

B.1- Piezoelectricity: Fundamentals.

The effect of piezoelectricity was discovered by Jacques and Pierre Curie in 1880 [172, 173]. This phenomenon, which consists on electrification when a pressure is applied, was found in materials like zinc blende, sodium chlorate, boracite, tourmaline, quartz and Roselle salt, among others [174]. The first practical application that took advantage of this effect happened during the World War I, when a big number of ships were lost due to German submarines. Then, it became crucial to find a way to locate those submarines. Paul Langevin designed an acoustic transducer composed by piezoelectric crystal quartz capable to generate acoustic waves in water [175] and receive the acoustic signal reflected in the seabed and in other objects. This was the first application of piezoelectricity and this can be considered as the birth of ultrasonics.

According to [79, 80], piezoelectricity is the name for the phenomenon whereby electric dipoles are generated in certain anisotropic crystals when subjected to mechanical stress. The same materials exhibit the converse effect in that they suffer a dimensional change under the influence of an electric field.

The concept of Curie temperature is important to understand the piezoelectric effect. This temperature sets the limit above which the crystal structure of the material has no electric dipole, meaning that no piezoelectric effect is present. Below the Curie temperature, the crystal structure

undergoes a phase change in which the crystal has a built-in electric dipole that can be reversed and switched in certain allowed directions by application of sufficiently high electric field.

Piezoelectric materials could be divided into a number of elements or domains in each of which the electric dipole is aligned in an allowed direction. It is necessary that the dipoles are aligned as shown in Fig. B. 1, by applying an electric field or a mechanical stress. So, in the case of piezoelectric materials, the process of dipole formation (or alignment of already existing permanent or induced dipoles) under the influence of an external electric field or mechanical stress is called polarization [176].

Fig. B. 1.- Representation of the electric dipoles of a piezoelectric material.

When the polarization process is completed, is not easy that the dipoles switch back to the initial direction, they remain aligned. The piezoelectric effect can be defined as the generation of an electric charge because of a force exerted on the material, while the inverse piezoelectric effect is defined as mechanical deformations produced by an electric voltage. Physically, an electric and a mechanic effect are related. The electric effect is explained in the Gauss' Theorem, which says that, when a non-conductor dielectric material is polarized, the internal dipoles are reoriented in the direction of the external electric field applied, obtaining a displacement of the charges of the dipoles and resulting into the appearance of a surface electric charge. If the piezoelectric ceramic has been shaped like a disk, the positive charge will appear in the polarization face and the negative charge in the opposite one

The mechanic effect is based on the Hooke's Law, which indicates that there is a linear relationship between the mechanical stresses applied in an elastic solid the deformation obtained. To take advantage of this effect, it became necessary to find a versatile piezoelectric material, which could be manufactured with almost any shape and with the direction of polarization freely chosen. This led industrial companies to use piezoelectric ceramics as the core of ultrasonic transducers instead of natural piezoelectric materials, because the latter need to be shaped while the piezoelectric ceramics are easy to mold, hence it is much cheaper for mass production. An example of these piezoelectric ceramics can be observed in Fig. B. 2.

Fig. B. 2.- Commercial piezoelectric ceramics.

In [177], the relation between electrical and mechanical properties are perfectly explained. In piezoelectric materials these properties are coupled and, therefore, they are involved in constituent relations. The mechanical relation involves the concepts of mechanical stress (T) and strain (S) by means of the Hooke's Law; and the electrical relation considers the electric field (E) and the dielectric displacement (D) by means of the Gauss' Theorem, as shown in Eq. B. 1 where s represents the elastic compliance and ϵ is the electrical permittivity.

$$\left. \begin{array}{l} S = sT \\ D = \epsilon E \end{array} \right\} \quad \text{Eq. B. 1}$$

Piezoelectricity involves the interaction between the electrical and mechanical behavior of the medium. This interaction can be described by the linear relations presented in Eq. B. 2:

$$\left. \begin{array}{l} D = dT + \epsilon^T E \\ S = s^E T + dE \end{array} \right\} \quad \text{Eq. B. 2}$$

Depending on the choice of independent variables (one mechanical and one electrical), other three pairs of linear relations describe the interaction between the mechanical and electrical parts. These relations are presented in Eq. B. 3 – Eq. B. 5:

$$\left. \begin{array}{l} E = -gT + \frac{1}{\epsilon^T} D \\ S = s^D T + gD \end{array} \right\} \quad \text{Eq. B. 3}$$

$$\left. \begin{array}{l} E = -hS + \frac{1}{\epsilon^S} D \\ T = c^D S - hD \end{array} \right\} \quad \text{Eq. B. 4}$$

$$\left. \begin{array}{l} D = eS + \epsilon^S E \\ T = c^E S - eE \end{array} \right\} \quad \text{Eq. B. 5}$$

The constants d , g , h and e are the piezoelectric constants and they can be defined from the equations. According to [79], only the strain piezoelectric relations Eq. B. 2 and Eq. B. 3 are commonly used, and then the constants d and g can be obtained clearing from the equations as a quotient of S and E or D and T in the first case, or a quotient of S and D or E and T in the second one. Eq. B. 4 and Eq. B. 5, related to stress, are rarely used, so the piezoelectric constants h and e are usually missing in material tables.

The main constants in Eq. B. 2 – Eq. B. 5 are then d , g , s^D , s^E , ϵ^T , ϵ^S . The superscripts denote the quantity that is kept constant in the boundary conditions. For example, s^D and s^E represent the specific elastic compliances for constant dielectric displacement and constant electric field respectively. On the other hand, ϵ^S and ϵ^T stands for the absolute permittivity (F/m) for constant strain and constant mechanical stress, respectively.

Piezoelectric materials, after polarization, lose their isotropic properties, becoming anisotropic materials. This means that the piezoelectric constants depend on the direction of stress, strain, electric field and electric displacement. To identify the directions involved in each constant, numeric subscripts are added. The subscripts 1, 2 and 3 corresponds to the directions X, Y and Z, with the last one referred to the poling direction; while the subscripts 4, 5 and 6 correspond to planes normal to directions 1, 2 and 3, respectively. This can be observed in Fig. B. 3.

Fig. B. 3.- Notation of axes.

According to this notation, we can find the following constants:

- Elastic constants: Compliance, s_{11} , s_{12} , s_{13} , s_{44} .
- Piezoelectric: d_{31} , d_{33} , d_{15} .
- Dielectric: Permittivity, ϵ_{11} , ϵ_{33} .

For example, the constant d_{31} corresponds to the ratio of strain in the 3-direction (poling direction) to the field applied in the direction 1; and the constant ϵ_{33} can be defined to the permittivity for the dielectric displacement and field for the direction 3.

It is important to pay attention to the parameter k , which is the coupling coefficient. Although this parameter cannot be considered as a measurement of efficiency of the piezoelectric material, it provides information about how the electro-mechanical or mechanic-electrical conversion takes place. The coupling coefficient is quantified as the square root of the relation between the input energy and the energy converted, as shown in Eq. B. 6:

$$k^2 = \frac{\text{energy converted}}{\text{input energy}} \quad \text{Eq. B. 6}$$

In the case of piezoelectric ceramics, the coupling factors that can be obtained, using the directional notation, are indicated in Eq. B. 7:

$$\left. \begin{aligned} k_{15} &= d_{15}/(s_{44}^E \varepsilon_{11}^T)^{1/2} \\ k_{33} &= d_{33}/(s_{33}^E \varepsilon_{33}^T)^{1/2} \\ k_{31} &= d_{31}/(s_{11}^E \varepsilon_{33}^T)^{1/2} \\ k_p &= d_{31}/[2/(s_{11}^E + s_{12}^E) \varepsilon_{33}^T]^{1/2} \\ k_t &= e_{33}/(\varepsilon_{33}^S c_{33}^D)^{1/2} \end{aligned} \right\} \quad \text{Eq. B. 7}$$

The parameters k_p and k_t are considered as special cases. Here, k_p is the planar coupling factor of a thin disk and refers to the coupling between the electric field in the poling direction (direction 3) and mechanical tension and compression in directions 1 and 2.

On the other hand, the parameter k_t is the thickness coupling coefficient between mechanical vibrations and electrical field in the direction 3, of a thin disk with arbitrary contour, where constraints apply in the large lateral dimensions.

Depending on the application for which the transducer is designed, the choice of a specific commercial piezoelectric ceramic is different. According to [178], the requirements of the piezoelectric ceramics used in the APUT under analysis in this work should be suitable for a transducer working at low frequency (between 20 kHz and 30 kHz) and in a high power regime, vibrating in a thickness mode. This implies that a high value of permittivity and elastic compliance is desirable to obtain adequate values for the electrical impedance [179].

The operational thickness mode appears at certain frequencies, as presented in Eq. B. 8 [180], where K_D is the stiffness constant for a constant electric displacement and b is the thickness of the ceramic disk. The longitudinal wave propagation velocity is presented in Eq. B. 9 [80]:

$$f_n = \frac{2n+1}{2b} \sqrt{\frac{K^D}{\rho}} \quad \text{Eq. B. 8}$$

$$c = \sqrt{\frac{1}{\rho s_{33}^D}} \quad \text{Eq. B. 9}$$

Another parameter that is important to consider is the Quality Factor (Q) that determines the efficiency and bandwidth (BW) of the ultrasonic system. In Macrosonics, it is desirable that the value of Q is as high as possible. This implies a resonant system with small energy losses. The value of the quality factor of a piezoelectric transducer operating at a determined frequency can be defined as the relation between the frequency and the bandwidth, as shown in Eq. B. 10:

$$Q = \frac{f}{BW} \quad \text{Eq. B. 10}$$

Table B. 1.- Properties of typical piezoelectric ceramics

Properties	Lead zirconate titanate (PZT)				
	PZT 4	PZT 5A	PZT 6B	PZT 7A	PZT 8
Coupling factors					
k_{33}	0.70	0.705	0.375	0.66	0.64
k_t	0.51	0.486	0.30	0.50	0.48
k_p	-0.58	-0.60	-0.25	-0.51	-0.51
Elastic compliances ($10^{-12} \text{ m}^2 \text{ N}^{-1}$)					
S_{33}^D	7.9	9.46	8.05	7.85	8.0
S_{33}^E	15.5	18.8	9.35	13.9	13.5
S_{11}^E	12.3	16.4	9.0	10.7	11.5
Dielectric constants					
$\epsilon_{33}^T/\epsilon_0$	1300	1700	460	425	1000
$\epsilon_{33}^S/\epsilon_0$	635	830	385	235	580
Piezoelectric constants ($10^{-12} \text{ C N}^{-1}$)					
d_{33}	289	374	71	150	225
d_{31}	-123	-171	-27	-60	-97
Quality factors					
Q_E	250	50	110	60	250
Q_M	500	75	1300	600	1000
Limiting data					
Curie point ($^{\circ}\text{C}$)	328	365	350	350	300
Rated dynamic tensile strength (10^7 Nm^{-2})	4	2.7	2.4	2.4	4.7
Stability data					
$\Delta s/\text{time decade} (\%)$	1.5	0.2	<0.1	-0.08	1.0
$\Delta \epsilon_{33}/\text{time decade}$	-5.8	-1	-0.6	2.0	-5.0
Characteristics and applications					
Characteristics	High coupling, high permittivity, good high-signal properties	High coupling, very high permittivity, high compliance	Very high mechanical Q value, good stability	Low permittivity	Very good high-signal properties
Applications	Sonar and macrosonics	Transducers for non-destructive testing and diagnostics, hydrophones	Electric wave filters	Ultrasonic delay lines	Power ultrasonic transducers

Among the piezoelectric materials that can be used for ultrasonic transducers, piezoelectric ceramics present the highest versatility in its design in terms of size, shape and elastic, electric and piezoelectric properties. And, among the piezoelectric ceramic materials, the most suitable for ultrasonic transducers is lead zirconate titanate (PZT) due to its strong piezoelectric properties, its high Curie point, and its versatility because small changes in its composition allow piezoelectric materials with different properties.

The PZT composites can be divided into two groups: soft and hard PZT's. The first group, soft PZT's, have large piezoelectric charge coefficients, moderate permittivity and high coupling factors (PZT 5A). The second group, hard PZT's, can be subjected to high electrical and mechanical stresses. They are defined by their moderate permittivity, large piezoelectric coupling factors, high quality, very good stability under mechanical loads and low dielectric losses (PZT 4 and PZT 8). Hard PZT's are used in power ultrasonics [181]. The mechanic, electric and piezoelectric constants of different types of PZT piezoelectric ceramics are presented in Table B. 1 [177].

B.2- Electrical and mechanical analogies of an APUT.

In order to understand the electrical theory regarding the behavior of an APU transducer, similarities between mechanical and electrical dynamics were analyzed, and some analogies were found [182, 183]. From the Newton's second law, the equation for a damped harmonic oscillator is presented in Eq. B. 11:

$$M \frac{d^2u}{dt^2} + R_m \frac{du}{dt} + ku = F \quad \text{Eq. B. 11}$$

Where M represents the mass of the particle, R_m is the damping ratio (or mechanical resistance) and k is the spring constant (the mechanical compliance is the inverse of the spring constant $C_m=1/k$). The particle displacement is defined by u and F represents the force applied to the system.

The Eq. B. 11 has an immediate analogy in the field of resonant electric circuits as can be observed in Eq. B. 12, where L represents the inductance, R is the electric resistance, C is the electrostatic capacity, q is the electric charge and E is the electromotive force:

$$L \frac{d^2q}{dt^2} + R \frac{dq}{dt} + \frac{1}{C} q = E \quad \text{Eq. B. 12}$$

Considering that the electric current (i) can be obtained deriving the electric charge ($i = \frac{dq}{dt}$), Eq. B. 12 can be rewritten as shown in Eq. B. 13, where each addend represents the voltage drop at each element of a series resonant circuit as shown in Fig. B. 4 [184]:

$$L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt = E \quad \text{Eq. B. 13}$$

Fig. B. 4.- Resonant series circuit.

According to Eq. B. 11 and Eq. B. 13, and considering that particle velocity $v = \frac{du}{dt}$, it is easy to identify the mechanical and electrical analogies, as presented in Table B. 2.

Table B. 2.- Mechanical and electrical analogies.

Mechanical magnitude	Electrical magnitude
M (mass)	L (inductance)
R_m (mechanical resistance)	R (resistance)
C_m (mechanical compliance)	C (capacity)
u (displacement)	q (electric charge)
v (velocity)	i (current)
F (mechanical force)	E (electromotive force)

B.2.1- Equivalent circuit of a piezoelectric transducer

The equivalent circuit for high Q transducers appears in [95]. This representation can be observed in Fig. B. 5:

a) Equivalent circuit

b) Simplification of this circuit

Fig. B. 5.- Equivalent circuit for ultrasonic transducers operating near resonance.

The equivalent circuit presented in Fig. B. 5.a includes the electrical part of the transducer, at the left of the electric transformer and the mechanical part at the right. The electrical side includes C_o that is the capacitance of the clamped transducer and R_o , which is the dielectric losses resistance. In the mechanical side of the circuit, R_r represents the radiation resistance, ψ is the electromechanical transformation factor and X_r the reactive component of the radiation impedance.

The circuit can be simplified in the form indicated in Fig. B. 5.b in which R_0 does not appear because its value generally is orders of magnitude greater than the other parallel branches. In this last circuit, L , C and R are given by Eq. B. 14

$$L = \frac{M + X_r/\omega}{\psi^2}; \quad C = C_m\psi^2; \quad R = \frac{R_m + R_r}{\psi^2} \quad \text{Eq. B. 14}$$

The values of the electric characteristics of the transducer (Admittance Y , Impedance $|Z|$ and C_0) can be obtained experimentally, with the help of an impedance analyzer, and theoretically, applying the equations presented in [95]. The equation of Conductance (G) and Susceptance (B) is obtained from the equation of admittance (Eq. B. 15), being the conductance the real part of the admittance and the susceptance the imaginary part.

$$Y = G + jB \quad Y = \frac{R}{R^2 + \left(\omega L - \frac{1}{C\omega}\right)^2} + j \left[\omega C_0 - \frac{\omega L - \frac{1}{C\omega}}{R^2 + \left(\omega L - \frac{1}{C\omega}\right)^2} \right] \quad \text{Eq. B. 15}$$

On the other hand, the values of R and C_0 can be deduced from the values of B and G when the transducer is vibrating in its resonance frequency (f_0) (Eq. B. 16).

$$R = \frac{1}{G_{max}} \quad C_0 = \frac{B(f_0)}{\omega_0} \quad L_0 = \frac{1}{\omega_0^2 C_0} \quad \text{Eq. B. 16}$$

The determination of C_0 is important because it must be compensated with a parallel inductance (L_0) whose value depends on the value of C_0 . This compensation is essential in the development of a dynamic resonance controller (DRC) that keeps the transducer working under resonance in a continuous operation.

B.3- Electronic excitation equipment.

In order to obtain higher vibration amplitudes, the transducer has to be excited in a resonance frequency. The resonance frequency may suffer displacements due to changes in the impedance of the transducer and the medium, heating of the different components of the transducer and of the surrounding medium, variations in density, etc. Hence, a variable frequency power generator is needed.

This continuous frequency adjustment can be done with an automatic controller based on a voltage controlled oscillator (VCO). The whole process is presented in [95]. The method for the dynamic tuning of ultrasonic transducer resonance is based on keeping constant at its zero value the phase of the motional admittance of the transducer by automatically adjusting the frequency of the driving signal provided by the VCO. The zero phase of the admittance can be achieved by setting the susceptance (B) to zero and, according to Eq. B. 16, this can be done by cancelling C_0 with the proper inductance L_0 . The block diagram of the DRC, as introduced in [95] is presented in Fig. B. 6.

Fig. B. 6.- Functional block diagram of the dynamic tuning procedure.

The tuning procedure is carried out by continuously taking samples of voltage and current at the input of the impedance matching and obtaining the phase difference between the two signals. The generator, based on a VCO, generates a sinusoidal signal whose frequency is continuously adjusted to find the minimum value of this phase. This allows the transducer to operate continuously under a resonance regime, even for transducers with a high quality factor.

Finally, it can be observed in Fig. B. 6 an impedance matching unit, responsible for achieving a good impedance matching between the output of the amplifier and the input of the transducer, in order to have a maximum power transfer between the two components. The maximum power transfer theorem says that, in reactive circuits, the internal impedance of the source and of the load should be complex conjugates of each other [185].

ANNEX C.- SIMULATION OF THE MECHANICAL PRESTRESS IN POWER ULTRASONIC TRANSDUCERS

The numerical model of power ultrasonic transducers corresponds to a multiphysics analysis, which includes Electrostatics and Structural Mechanics physics in COMSOL Multiphysics®.

Considering only the vibrator of the transducer, this is composed of a Langevin type sandwich and a mechanical amplifier or horn. The Langevin transducer is composed of two stacks of two piezoelectric ceramics separated by a brass flange and two attached steel masses. When the transducer is excited with an electric voltage, the ceramics experience a piezoelectric effect and change its size according to the electric excitation. An alternate current provokes a mechanical vibration of the ceramics, which is transmitted to the rest of the components of the transducer.

The piezoelectric ceramics used in power transducers for industrial applications are exposed to high voltages, which may lead to high strains. These strains can provoke breakages in the ceramics. A mechanical prestress caused by a central bolt compresses the ceramics and allows strains without higher amplitudes minimizing the risk of fractures [79]. The application of this prestress, depending on its magnitude, may cause changes in the behavior of the transducer [81]. The numerical analysis of the prestress done in this work corresponds to an ultrasonic transducer working at around 21 kHz. The magnitude of the simulated prestress is 25 MPa in the ceramics [46]. In this case, a slight frequency shift is expected compared to the system without this prestress [81].

C.1- Simulation of the mechanical prestress in 3D models.

The 3D model of the vibrator used as an example of this work is shown in Fig. C. 1, where it can be observed the two piezoceramic stacks separated by a brass flange, the back and front masses, the horn and the central bolt, in charge of applying the required prestress. This model corresponds to a symmetric model, with the simulations carried out only in half of the system.

When working in a 3D model, the application of a prestress does not imply a high difficulty. After defining the bolt using the parts library in the geometry node, we can use the “Bolt-Pretension” node in the Solid Mechanics physic, and there we can define the magnitude of this prestress.

In order to define and apply the prestress to the transducer, a two steps simulation has to be done in an Eigenfrequencies or Frequency Domain study. The first step is a stationary simulation, under an open-circuit electrical condition (only the negative poles of the ceramics are connected to ground and positive poles are left free). The magnitude of the pretension should guarantee a mechanical prestress of 25 MPa in the piezoceramics [46], as shown in Fig. C. 2.

Fig. C. 1.- 3D model of the vibrator used in the prestress analysis.

a) 3D cut line where the prestress is calculated b) Magnitude of the Von Mises stress along the 3D cut line
Fig. C. 2.- Pretension obtained in the piezoceramic stack.

The second step is a dynamic analysis, in which the results obtained in the previous step have to be considered as input data. The way to do this is considering the geometric nonlinearity on the second step and defining a linear perturbation in the stationary solver, using the previously stored solution in the new one. The configuration of the stationary solver is shown in Fig. C. 3.

C.1.1- Eigenfrequency analysis.

The operational mode of the Langevin transducer is a thickness mode of the ceramics and an extensional mode in the horn, where displacement amplification takes place.

An eigenfrequency study has been done in order to find the frequency where this operational mode takes place. This study has been carried out for the two situations, without and with prestress, obtaining a frequency displacement of around 600 Hz (27731 Hz in the case of a transducer without prestress, and 27138 Hz for the simulation with prestress) when applying the prestress. The displacement obtained in both situations can be observed in Fig. C. 4.

Fig. C. 3.- Configuration of the stationary solver in the Frequency Domain study.

Fig. C. 4.- Extensional mode of the transducer.

All these simulations are composed of a static and a dynamic component. The final solution comprises both of them and the contribution of the static and dynamic parts can be observed in every simulation. These contributions to the eigenfrequency determination can be seen in Fig. C. 5, where it is easy to appreciate how the bolt pretension provokes a displacement in the whole transducer, and how the extensional mode achieves maximum values of displacement in the tip of the horn.

a) Static contribution to the total displacement. b) Dynamic contribution
Fig. C. 5.- Contribution of the static and dynamic components.

C.1.2- Frequency domain study.

A frequency domain analysis around resonance has been done, applying a voltage of 10V to the ceramics, in order to determine the maximum displacement at the tip of the mechanical amplifier (Fig. C. 6.a) and the amplification achieved in the horn (Fig. C. 6.b):

a) Maximum displacement at the tip. b) Displacement amplification in the horn.
Fig. C. 6.- Frequency domain analysis.

As it can be observed in Fig. C. 6.a, the stationary step, the prestress, applies a fixed displacement in the whole frequency range that reduces the maximum displacement at the tip, as can be observed in Fig. C. 6.b, where the system without prestress achieves a displacement of 120 μm and the system with prestress has a maximum of about 11 μm .

It can be seen in Fig. C. 6.b that the displacement provoked by the pretension also implies a smaller displacement at the tip and amplification in the horn.

Finally, one of the main objectives of applying this pretension is to avoid high values of mechanical stress when applying power. In Fig. C. 7, the differences in terms of stress can be observed. The transducer without prestress suffers values of mechanical stress higher than 500 MPa in the horn, while the prestressed system has maximum values of 300 MPa in the bolt and less than 100 MPa in the horn:

C.2- Simulation of the mechanical prestress in 2D axisymmetric models.

The simulation of the mechanical prestress in 2D axisymmetric models entails more difficulties than the simulation of this prestress in 3D models. 2D models do not allow the possibility to define a bolt with the required prestress, but it is necessary to do this “manually”.

The model used to show the simulation of the mechanical prestress corresponds to the vibrator of an airborne power ultrasonic transducer with an operational frequency around 26 kHz. This model is presented in Fig. C. 8.

Fig. C. 8.- 2D axisymmetric model of the vibrator used in the prestress analysis.

The four ceramics are highlighted in green, while the bolt that tightens the components of the Langevin transducer is highlighted in red. The Langevin transducer and the mechanical amplifier are also tightened using a set screw, which is highlighted in blue.

The M10 bolt is the element that provides the required mechanical prestress to the ceramic stack. As mentioned before, a stress of about 25 MPa in the ceramics seems to be adequate [46]. Nevertheless, for a 2D axisymmetric model, COMSOL Multiphysics does not permit the definition of a bolt and the indication of a value of mechanical prestress. To simulate the prestress, the model of the bolt has been sliced in its central part, as it can be observed in Fig. C. 8. Two lines

divide the bolt into three parts. This is a technical division, meaning that the simulated bolt is still one domain, and the divisions are only for simulation purposes.

So, one way to simulate the mechanical prestress is to apply “Boundary Loads” to those divisions with the same value and opposite directions, as shown in Fig. C. 9.

Fig. C. 9.- Application of the boundary load for the mechanical prestress

The value of the boundary load has to be calculated to obtain the desired 25 MPa prestress in the ceramics, as shown in Fig. C. 10.

The rest of the process for this simulation is similar as 3D models, where a double simulation is required, an initial stationary calculation, which obtains the effects of the prestress, and a second step that incorporates the results of the stationary study as input data, by considering the geometric nonlinearity and defining a linear perturbation in the stationary solver, using the previous stored solution in the new one (see Fig. C. 3).

a) Definition of the line where the prestress is defined b) Von Mises stress along the defined line
Fig. C. 10.- Prestress obtained in the ceramics of a 2D axisymmetric simulation.

It is important to take into account that a Boundary Load in a Frequency Domain calculation is subjected to a harmonic perturbation when carrying out this simulation. This means that the prestress would be modulated by a harmonic wave, corresponding to the operational frequency under study. The correct procedure consists on disabling the boundary loads corresponding to the prestress definition in the second step of the simulation (Frequency Domain or Eigenfrequencies

studies). This can be observed in Fig. C. 11, which shows the physics tree in a Frequency Domain study, where the boundary loads corresponding to the prestress are disabled.

Fig. C. 11.- Configuration of the physics tree of the Frequency Domain study.

Following these steps, the simulation of the prestress can be correctly done. The results of this 2D axisymmetric study are presented in Chapter 3, corresponding to the numerical simulation of airborne power ultrasonic transducers.

ANNEX D.- ADDITIONAL RESULTS OBTAINED IN THE NUMERICAL SIMULATIONS OF AIRBORNE POWER ULTRASONIC TRANSDUCERS

D.1- Mode shapes corresponding to the different eigenmodes of the vibrator tuned around 26 kHz.

This Annex shows the mode shapes corresponding to the operational extensional mode of the vibrator tuned at around 26 kHz, and other modes obtained numerically. All these modes are presented in Fig. D. 1, and correspond to a 3D view of the harmonic contribution to the natural vibration of the transducer at each eigenfrequency.

Fig. D. 1.- Eigenmodes of the vibrator tuned at 26 kHz.

D.2- Mode shapes corresponding to the different eigenmodes of the stepped-grooved circular radiator.

This section shows the mode shapes corresponding to the natural modes of the stepped-grooved circular radiator that are located near the operational mode corresponding to a flexural vibration with seven nodal circles. All these modes are presented in Fig. D. 2, and correspond to a 3D view of the natural vibration of the circular plate at each eigenfrequency:

Fig. D. 2.- Eigenmodes of the stepped-grooved circular radiator.

D.3- Mode shapes corresponding to the different eigenmodes of the APU transducer with stepped-grooved circular radiator.

This section shows the mode shapes corresponding to the natural modes of the APT transducer with stepped-grooved circular radiator located near the operational mode corresponding to a flexural vibration with seven nodal circles.

Fig. D. 3.- Eigenmodes of the APUT with stepped-grooved circular plate.

D.4- Mode shapes corresponding to the different eigenmodes of the vibrator tuned around 21 kHz.

This section shows the mode shapes corresponding to the natural modes of the vibrator tuned at 21 kHz that are located near the operational extensional mode. All these modes are presented in Fig. D. 4, and correspond to a 3D view of the natural vibration of the system:

Fig. D. 4.- Eigenmodes of the vibrator tuned at 21 kHz.

D.5- Mode shapes corresponding to the different eigenmodes of the flat rectangular radiator.

This section shows the mode shapes corresponding to the natural modes of the flat rectangular radiator that are located near the operational mode corresponding to a flexural vibration with twelve nodal lines. All these modes are presented in Fig. D. 5, and correspond to a 3D view of the natural vibration of the rectangular plate at each eigenfrequency.

Fig. D. 5.- Eigenmodes of the flat rectangular radiator.

D.6- Mode shapes corresponding to the different eigenmodes of the APU transducer with flat rectangular radiator.

This section shows the mode shapes corresponding to the natural modes of the flat rectangular radiator that are located near the operational mode corresponding to a flexural vibration with twelve nodal lines. All these modes are presented in Fig. D. 6, and correspond to a 3D view of the natural vibration of the rectangular plate at each eigenfrequency.

Fig. D. 6.- Eigenmodes of the APUT with flat rectangular radiator.

ANNEX E.- PHYSICAL PROPERTIES OF THE MATERIALS

Table E. 1.- Physical properties for the components of the different transducers

Component	Magnitude	Value
Piezoelectric ceramics (stress-charge form)	Material	PZT 8
	Density (ρ)	7600 kg/m ³
	Sound speed (c)	4056 m/s
	Elastic compliance (s_{33}^D)	$8 \cdot 10^{-12}$ m ² /N
	Elasticity matrix (c_E)	$\begin{bmatrix} 14.6876 & 8.10870 & 8.10537 & 0 & 0 & 0 \\ 8.10870 & 14.6876 & 8.10537 & 0 & 0 & 0 \\ 8.10537 & 8.10537 & 13.1712 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.1348 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.1348 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.28947 \end{bmatrix} \cdot 10^{10} \text{ Pa}$
	Coupling matrix (e)	$\begin{bmatrix} 0 & 0 & -3.87538 \\ 0 & 0 & 3.87538 \\ 0 & 0 & 13.9108 \\ 0 & 10.3448 & 0 \\ 10.3448 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{ C/m}^2$
	Relative permittivity (ϵ_r^S)	$\begin{bmatrix} 904.4 & 0 & 0 \\ 0 & 904.4 & 0 \\ 0 & 0 & 561.6 \end{bmatrix}$
Back mass and front mass	Material	Stainless steel AISI 420
	Density (ρ)	7715 kg/m ³
	Young Modulus (Y)	$2.187 \cdot 10^{11}$ Pa
	Poisson ratio (ν)	0.28
	Sound speed (c)	6020 m/s
	Yield strength	345 MPa [186]
Central bolt	Material	Steel F-1250 (Spanish code for AISI 4135-4137)
	Density (ρ)	8250 kg/m ³
	Young Modulus (Y)	$2.076 \cdot 10^{11}$ Pa
	Poisson ratio (ν)	0.288
	Yield strength	450 MPa [187]

Brass flange	Material	Brass
	Density (ρ)	8350 kg/m ³
	Young Modulus (Y)	$9.27 \cdot 10^{10}$ Pa
	Poisson ratio (ν)	0.365
Mechanical amplifier	Material	Titanium
	Density (ρ)	4423 kg/m ³
	Young Modulus (Y)	$1.17 \cdot 10^{11}$ Pa
	Poisson ratio (ν)	0.32
	Sound speed (c)	5143 m/s
	Yield strength	830 MPa [111]
Bolt M10	Material	Titanium Alloy (Ti6Al4V)
	Density (ρ)	4414 kg/m ³
	Young Modulus (Y)	$1.12 \cdot 10^{11}$ Pa
	Poisson ratio (ν)	0.326
	Sound speed (c)	5037 m/s
	Yield strength	830 MPa [111]
Stepped-grooved circular plate	Material	Titanium Alloy (Ti6Al4V)
	Density (ρ)	4414 kg/m ³
	Young Modulus (Y)	$1.12 \cdot 10^{11}$ Pa
	Poisson ratio (ν)	0.326
	Sound speed (c)	5328 m/s
	Yield strength	830 MPa [111]
Rectangular plate	Material	Aluminum Alloy (7022)
	Young Modulus (Y)	$7.06 \cdot 10^{10}$ Pa
		$7.06 \cdot 10^{10}$ Pa
		$6.88 \cdot 10^{10}$ Pa
	Poisson ratio (ν)	0.342
		0.342
		0.346
	Density (ρ)	2760 kg/m ³
	Sound speed (c)	5321 m/s
	Yield strength	400 MPa [186]

ANNEX F.- DESIGN OF AN ADAPTATIVE MECHANICAL AMPLIFIER FOR RECTANGULAR RADIATORS. TABLES AND FIGURES

F.1- Vibration modes near the operational one with two nodal lines.

Fig. F. 1.- Other undesired modes.

F.2- Numerical simulation of the airborne power ultrasonic transducer with the five adapters.

F.2.1- Adapter with circular shape

The first adapter chosen had a circular shape, and it would be considered as a prolongation of the narrow section of the horn. In this numerical analysis, the most adequate radius of the adapter has been chosen in terms of maximum vertical displacement in the rectangular plate and minimum stress suffered by the transducer.

For this simulation, a parametric analysis has been done, modifying the radius of the circular adapter between 9 mm and 15 mm in steps of 0.5 mm. The eigenfrequencies analysis indicates that the operational mode increases its natural frequency when the radius is bigger. The flange mode remains at the same frequency (18956 Hz). It can be seen in Fig. F. 2 how the separation between the operational mode and other near modes increases with the radius of the adapter.

The result of the frequency domain analysis is presented in Fig. F. 3, with the normalized amplitude of displacement and mechanical stress calculated for each radius of the circular adapter.

Several conclusions are obtained from this simulation. The first one is that there are high differences between different sizes for the adapters. The adapter with radius of 12 mm shows a much higher displacement amplitudes and stresses; this might imply a good efficiency, but also higher risk. The choice of the adapter should come from an element that provides a good relationship between displacements achieved and stress suffered by the transducer. According to

this, the circular adapter with a radius of 10.5 mm presented a good behavior, so it has been chosen for the experimental study.

Fig. F. 2.- Evolution of the natural frequencies with the radius of the circular adapter.

a) Normalized displacement

b) Normalized mechanical stress

Fig. F. 3.- Results of the numerical simulation of the transducer with circular adapter.

F.2.2- Adapter with long-rounded shape

The next shape is a long-rounded shape, with a section composed by a square element and semicircles in two sides. Because of the non-axisymmetric pattern of this adapter, its orientation (parallel or perpendicular) respect the nodal lines of the radiator at its working mode has been studied in the initial steps.

The physical characteristics of the rectangular radiator and the operational mode with two longitudinal nodal lines (Fig. 5.45) implies a high interaction between the long adapter and the vibration mode of the plate if there is a transversal relation between the nodal lines and the adapter. This interaction affects the generation of the ultrasonic field and invalidates its performance. This interaction can be observed in Fig. F. 4, where overhead views of the radiator, with the vibration contours are presented, for different sizes of the adapter, place in parallel and perpendicular to the nodal lines:

Fig. F. 4.- Contour of the vibration mode produced by different long adapters

In this case, the interaction between the adapter and the operational mode of the transducer is important, modifying the performance of the system when they are in perpendicular direction (Fig. F. 4.b and Fig. F. 4.d). The next analysis has been done considering that the adapter is situated in parallel with the nodal lines.

The one of the sides of the adapter is 18 mm long, while the other side (denominated as b-side) varies between 14 mm and 28 mm. The semicircles have a radius of 9 mm. The adapter is 10 mm thick. The dimensions can be observed graphically in Fig. F. 5.

a) Dimensions of the long adapter

b) Position of the adapter

Fig. F. 5.- Physical characteristics of the long-rounded adapter

The parametric eigenfrequency analysis has been done for a range between 14 mm and 28 mm in the variable length (b-side), in steps of 1 mm. The corresponding frequencies of the eigenmodes for each configuration are shown in Fig. F. 6.

Fig. F. 6.- Evolution of the natural frequencies with the length of the long-rounded adapter.

There is an undesired flange mode at 18956 Hz in all cases, and the working mode with two nodal lines moves slightly its eigenfrequency when the b-side increases. Nevertheless, this frequency displacement is smaller in this case than in the case of the circular adapter.

The numerical simulation of the mechanical performance of the transducer has been done under the lineal regime, with a voltage of 20 V at the working frequency. The comparison between the different configurations is presented in Fig. F. 7, with the normalized amplitude of displacement and mechanical stress calculated for each value of the b-side of the long rounded adapter.

Fig. F. 7.- Results of the numerical simulation of the transducer with long-rounded adapter.

The numerical analysis indicates that some values of the b-side contribute to higher displacements of the plate, for example values of 14 mm, 26 mm and 27 mm. Rejecting the values that provide minimum displacements, few configurations seem to be useful for this purpose. In this case, two sizes has been chosen, the size that provides higher displacements, 14 mm for the b-side (known as short-rounded), and the adapter with a value of the b-side of 26 mm (known as long-rounded), that also provides high displacements, but with lower stresses.

F.2.3- Adapter with squared shape

The following adapter has a squared shape. When metallic elements are subject to high mechanical stresses, straight edges are usually weaknesses of the systems. Because of this reason, the edges of the adapters are chamfered.

The numerical simulation to define the square adapter to use in the experimental research has consisted on a parametric study for squares with sides between 14 mm and 28 mm in steps of 1 mm. The location of the natural modes of the system is presented in Fig. F. 8, where a similar behavior as the other adapters is observed. There is a flange mode at 18943 Hz in all cases, and the working mode changes its frequency, separating it from the undesired flange mode when the side of the square increases.

The flange mode happens at 18943 Hz, and the working mode with two nodal lines increases its eigenfrequency with the side of the square. The numerical simulation of the mechanical performance of the transducer has been done under the lineal regime, with a voltage of 20 V at the working frequency. The comparison between the different configurations is presented in Fig. F. 9, with the normalized amplitude of displacement and mechanical stress calculated for each value of the side of the squared adapter.

Fig. F. 8.- Evolution of the natural frequencies with the side length of the squared adapter.

According to the results obtained after the numerical analysis, several values of the side of the square are responsible for higher displacements and mechanical stresses suffered by the different components analyzed. The squared adapter with a side of 25 mm seems to provide a good value of displacement with reasonable value of mechanical stress in the plate and in the horn. This is the size chosen for the experimental study.

Fig. F. 9.- Results of the numerical simulation of the transducer with squared adapter.

F.2.4- Adapter with rectangular shape

Finally, the rectangular is the last shape for the adapter of the mechanical amplifier studied. This is a more complex simulation because the two dimensions of the rectangular shape have been analyzed. This implies a parametric study that simulates all the combinations obtained varying the two sides from 14 mm to 28 mm, in steps of 1 mm.

As it happened in the case of the long-rounded shapes, the configurations where the mechanical adapter is placed in a perpendicular direction from the nodal lines have been discarded because, at least in this case, the vibration shape of the plate has been modified, as it is shown in Fig. F. 10.

Fig. F. 10.- Contour of the vibration mode produced by a 27x21 mm rectangular adapter.

Considering this, the parametric study has been limited to the configurations of the adapter that implies a parallelism between this piece and the shape of the working mode of the plate. The frequency location of each mode is presented in Fig. F. 11, where 14 series of data, corresponding to the dimension of the side, parallel to the nodal lines, of the adapter, are represented, identifying the frequency in which each natural mode happens, depending also on the size of the perpendicular side of the rectangular adapter.

It can be observed the same behavior than other adapters, with a flange mode that happens, in this case, at 18943 Hz, and a varying operational mode, which increases its natural frequency when the adapter is increasing its dimensions.

Fig. F. 11.- Evolution of the natural frequencies with the dimensions of the rectangular adapter.

The numerical study of the mechanical behavior of the transducer, working at the operational frequency for each configuration, is presented in Fig. F. 12. As mentioned before, this simulation is more complex because there are two variables to consider: the two dimensions of the rectangular adapter. Because of that, the representation of the normalized mechanical stress has been divided into three graphics, one for each component considered (plate, bolt and horn).

b) Normalized mechanical stress in the rectangular plate

c) Normalized mechanical stress in the bolt

d) Normalized mechanical stress in the mechanical amplifier

Fig. F. 12.- Results of the numerical simulation of the transducer with rectangular adapter.

As shown in Fig. F. 12, there are several configurations that allow higher values of displacement (16x14 mm, 23x19 mm, 27x21 mm and 27x26 mm). The values of the mechanical stress suffered by the transducer are also high. Nevertheless, the adapters with dimensions 27x21 mm and 27x26 mm provide a better relationship between displacement and stress. Considering that the adapter with size 27x26 mm is almost a square, the chosen configuration for the experimental study has been a rectangular adapter with dimension 27x21 mm.

ANNEX G.- DESCRIPTION OF THE TWO DYNAMIC CHARACTERIZATION SYSTEMS

G.1- Old system for the nonlinear dynamics characterization of APU transducers

This first system was presented in [188], and it is composed by a power generator, impedance matching unit, data acquisition unit, computer with the Labview[®] application developed for this purpose, and, of course, the APU transducer. The power generator is composed by a signal generator, an ultrasonic controller and a power amplifier. The signal generator and the ultrasonic controller operate in different configurations. The first is capable to generate signals according the provided parameters (frequency sweeps, different waveforms for continuous signals, amplitude, etc.) while the second allows the transducer to operate under resonance conditions by keeping in phase the voltage (V) and the current signals (I). The block diagram of this characterization system can be observed in Fig. G. 1 [188].

Fig. G. 1.- Block diagram of the previous dynamic characterization system.

G.2- New system for the nonlinear dynamics characterization of APU transducers

The block diagram of this new characterization system can be observed in Fig. G. 2.

Fig. G. 2.- Block diagram of the new dynamic characterization system.

The computer is connected via USB to the signal generator (Tektronix AFG3252), capable of generating the desired excitation signal with a high frequency resolution (higher than 0.1 Hz). This signal is sent to the power amplifier with two bridged channels in order to supply high power.

The impedance matching unit adapts the excitation signal to the impedance of the transducer, like in the case of the stability tests. Nevertheless, the impedance matching unit used for these studies is adaptive, meaning that the output impedance can be modified according to the characteristics of the transducer.

It has been mentioned that the efficiency of the whole system depends, among other aspects, on the impedance matching between the excitation signal and the ultrasonic system. Depending on the type of transducer considered, its impedance may vary between less than 50 Ω in sonotrodes and more than 500 Ω in transducers with extensive radiators, or much higher impedance values for transducers with very extensive plates.

The signal that leaves the impedance matching unit is suitable to excite the transducer in the desired frequency and voltage (or power). The current and voltage are monitored and can be kept around the required value and below the limit values defined in the application. The signal generator and the adaptive impedance matching unit can be seen in Fig. G. 3.

a) Signal generator
b) Adaptive impedance matching unit
Fig. G. 3.- Components of the generation system for the dynamics characterization system.

The response of the transducer is then measured electrically, at the output of the impedance matching unit; mechanically, with the laser vibrometer (Polytec OFV 3001S), that measures the vibration velocity (or displacement) in the extensive radiator surface; and thermally, with an infrared sensor that acquires temperature increases in the desired area of the transducer. Additionally, acoustic measurements can also be done with a $\frac{1}{8}$ " microphone, placed in the near field, that allows the measurement of the acoustic spectrum.

All these signals (voltage (V), current (I), vibration velocity ($\dot{\xi}$), sound pressure (Pa) and temperature (T)) are connected to a multichannel simultaneous S/H (signal and hold) data acquisition unit and then to a PXI platform that allows faster communications with the computer. The 1D vibrometer laser and the PXI platform can be seen in Fig. G. 4:

a) 1D vibrometer laser
b) PXI platform
Fig. G. 4.- Components of the acquisition system of the dynamics characterization system.

It is necessary to mention that with this characterization system, an oscilloscope is no longer necessary because the application allows multi-domain analysis, so frequency and time domain analysis can be performed simultaneously.

The main goal of this nonlinear dynamics characterization system is to provide a way of performing different tasks simultaneously: signal acquisition, analysis, characterization, control, monitoring and data logging. The application, based in Labview, offers an enhanced effectiveness, comfort and speed in the tests, versatility, mistakes reduction, and it makes no longer necessary the changes in the physical configuration for different kind of tests or type of loads.

Also, the program prevents the different parts from being damaged by high voltage, current or temperature by a maximum allowed value that can be selected by the user.

Most of the configurations are performed applying software solutions. For example, there is no longer necessary to connect a physical inductance (L) to compensate the parallel capacity (C_0) when tracking resonance, only by choosing the required compensation in the program. This allows the distortion reduction in the impedance matching unit output.

Compensation of the interelectrode capacitance. The electromechanical analogies can be used to describe and analyze some types of systems, meaning its mechanical model or its equivalent electric circuit under resonance conditions.

The simplest system in piezoelectric transducers is composed by a quadripole (or a two port network) with two ports, an electrical one and a mechanical one. The input electrical port, a voltage source generates an electric current toward the transducer. In the output mechanical port, the applied force provokes a vibration of the system with a displacement velocity. The intensity of the electrical branch is directly related to the displacement in the mechanical branch.

The mechanical branch of the transducer, working under resonance conditions, is like a harmonic oscillator with losses, composed by a mass (M_m), a mechanical compliance (C_m) and mechanical resistance (R_m); or like its equivalent RLC electric circuit, composed by an inductance (L), a capacitance (C) and electric resistance (R). So, the displacement velocity ($\dot{\xi}$) of a mechanic oscillator subjected to an external force behaves like the current intensity of a RLC series circuit subjected to an external voltage, provided that M_m , C_m and R_m are analogous to L , C and R , respectively.

On the other hand, and due to the capacitive behavior of piezoelectric ceramics, a parallel interelectrode capacity (C_0) has to be added to this RLC equivalent model, as it can be observed in Fig. G. 5.

The circuit shown in Fig. G. 5.b, the reactive elements (C , L) store the energy no transmitted to the medium, the only transmitted energy comes from the resistance R , whose value is $R = R_p + R_R$. The resistance is composed by two parts: R_p , which represents resistance losses due to mechanical friction; and R_R , which is the radiation resistance. The dissipated power in R_R is

transmitted to the medium as ultrasonic waves. When the transducer works under resonance, the capacitance C and the inductance L of the mechanical branch are compensated and, therefore, cancelled. Because of this reason, the RLC circuit is transformed into a purely resistive system. Nevertheless, the parallel capacitance (C_0) remains and makes it necessary to add a parallel inductance L_0 between the generator and the transducer to obtain maximum power transfer, as it can be observed in Fig. G. 6.

Fig. G. 6.- Equivalent circuit of a transducer under resonance condition.

This new system has been developed to add this compensation inductance (L_0) virtually, for the analysis of the obtained results, simulating the behavior of the transducer when different compensations are applied. This tool allows the determination of the most adequate compensation for each configuration.

For example, the virtual determination of the L_0 of the APUT with flat rectangular plate has been done by generating a 1D frequency sweep around resonance (21138 Hz), with a continuous excitation of 100 V.

The parameter analyzed for the determination of the parallel capacity is the admittance (Y) of the transducer, which has been modified, applying (by software) different values of the compensation inductance (L_0). The series of graphics can be observed in Fig. G. 7.

The compensated curves are drawn in solid green line. The three compensated curves have different appearance, but the most symmetric curve is the one obtained with a value $L_0 = 9$ mH, which seems to be the most adequate in this case.

Resonance tracking. To guarantee that the APU transducer is capable to provoke the desired effects when working under a high power regime (effects like mass transfer enhancement, particle agglomeration, defoaming, etc.) is necessary the system to vibrate under resonance in the required vibration mode during the whole operation period.

Commonly, the resonance frequency experiences displacements to lower frequencies during continuous operation because of the heating of the piezoelectric ceramics (softening effect), so, the generation system has to change the excitation frequency with these variations. The resonance tracking is usually performed with an ultrasonic controller, as in the case of the old characterization system.

Fig. G. 7.- Measurement of the admittance and virtual compensation of C_0 .

In the new system, the resonance tracking is performed completely by software, applying traditional algorithms (maximum power and minimum phase), but monitoring all the events and giving a total flexibility and fast reprogramming (changes in C_p compensation, frequency range, tolerances...).

Functionalities. Finally, regarding the transducer characterization, we can find the following functionalities:

- Quality factor (Q) characterization.
- Automatic obtainment of local minimums and maximums.
- Automatic modeling applying analytical functions, linear, polynomial or exponential.
- Different curves, for different compensation criteria.
- Multi-domain analysis.
- Isothermal analysis.
- Response characterization based on voltage or power variations.
- Datalogging.
- Graphics export.

All these tools, among others, allow a dynamic, fast and economic analysis of the nonlinear behavior of airborne power ultrasonic transducers for different purposes.

G.3- Comparison between the two systems for the nonlinear dynamics characterization of the APUT

The comparison between the two characterization systems has been done for the APU transducer with a flat rectangular radiator, vibrating in a flexural mode with twelve nodal lines. This comparison has been made for a 2D sweep around the resonance and for different excitation voltages. The figures shown correspond to the vibration velocity ($\dot{\xi}$) obtained with the 1D laser vibrometer pointing at a maximum displacement area, near the border of the radiator.

For this analysis, two settings has been considered, a continuous signal excitation and a burst configuration, in order to separate the nonlinear behavior due to thermal effects from the nonlinear behavior due to the transducer itself. These results are presented in Fig. G. 8.

Fig. G. 8.- Comparison between the two systems for the nonlinear dynamic characterization.

Both systems show a slight hardening effect when applying continuous excitation signal and softening when applying burst. The values of the vibration velocity and frequency shifts in both systems are similar, but the new system offers a more deterministic behavior, as it can be seen for burst excitation, where the curves show a monotonic performance. So, the new system offers a more accurate behavior and a better performance.

ANNEX H.- PUBLICATIONS

H.1- Journal papers.

- R. R. Andrés, V. M. Acosta, M. Lucas, and E. Riera, "Modal analysis and nonlinear characterization of an airborne power ultrasonic transducer with rectangular plate radiator," *Ultrasonics*, vol. 82, pp. 345-356, 2018/01/01/ 2018.
- R. R. Andrés, A. Pinto, I. Martínez, and E. Riera, "Acoustic field generated by an innovative airborne power ultrasonic system with reflectors for coherent radiation," *Ultrasonics*, p. 105963, 2019/07/15/ 2019.
- R. R. Andrés, E. Riera, J. A. Gallego-Juárez, A. Mulet, J. V. García-Pérez, and J. A. Cárcel, "Airborne power ultrasound for drying process intensification at low temperatures: Use of a stepped-grooved plate transducer," *Drying Technology*, pp. 1-14, 2019.
- R. R. Andrés, E. Riera, " Application of the Caldersmith expression for the study of rectangular radiators for power ultrasonic transducers," *International Journal of Acoustics and Vibrations* (in press).

H.2- Book chapters.

- J. A. Gallego-Juárez , G. Rodríguez , E. Riera, R. R Andrés and A. Cardoni, "Chapter 7 - Power ultrasonic transducers with vibrating plate radiators," in *Power Ultrasonics 2nd Edition*, ed Oxford: Woodhead Publishing, (in press).
- J. V. García-Pérez, J. A. Carcel, A. Mulet, E. Riera, R. R. Andres and J. A. Gallego-Juarez, "Chapter 29 - Ultrasonic drying for food preservation," in *Power Ultrasonics 2nd Edition*, ed Oxford: Woodhead Publishing, (in press).

H.3- Conference papers.

- R. R. Andrés, A. Blanco, V. M. Acosta, E. Riera, I. Martínez, and A. Pinto, "New ultrasonic controller and characterization system for low temperature drying process intensification," *Physics Procedia*, vol. 70, pp. 833-836, 2015.
- R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "Description of an ultrasonic technology for food dehydration process intensification," *Proceedings of Meetings on Acoustics*, vol. 28, p. 045003, 2016.
- E. Riera, V. M. Acosta, J. Bon, M. Aleixandre, A. Blanco, R. R. Andrés, et al., "Airborne Power Ultrasonic Technologies for Intensification of Food and Environmental Processes," *Physics Procedia*, vol. 87, pp. 54-60, 2016/01/01/ 2016.

- R. R. Andrés, E. Riera, J. A. Gallego-Juárez, J. A. Cárcel, and J. V. García-Pérez, "State-of-the-art in the application of airborne power ultrasonic technologies in atmospheric freeze drying processes," *Proceedings of Meetings on Acoustics*, vol. 38, p. 032005, 2019.
- R. R. Andrés, A. Pinto, J. A. Cárcel, and E. Riera, "Airborne power ultrasonic transducers with stepped circular radiator for lyophilization at atmospheric pressure," *Proceedings of Meetings on Acoustics*, vol. 38, p. 030011, 2019.

H.4- Contributions in international conferences and symposiums.

- R. R. Andrés, O. Louisnard, E. Riera, and V. M. Acosta, "Study of the near field generated by a power ultrasonic transducer," in *Euroregio 2016, Porto (Portugal)*, 2016.
- R. R. Andrés, O. Louisnard, E. Riera, and V. M. Acosta, "Numerical analysis of an ultrasonic technology for food dehydration process intensification," in *COMSOL Conference, Munich*, 2016.
- R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "New ultrasonic technologies for food dehydration process intensification," in *22nd International Congress on Acoustics (ICA), Buenos Aires (Argentina)*, 2016.
- R. R. Andrés, V. M. Acosta, O. Louisnard, and E. Riera, "Effect of the design of the mechanical amplifier in the behavior of a high power ultrasonic transducer," in *Euroregio 2016, Porto (Portugal)*, 2016.
- R. R. Andrés and E. Riera, "Considerations regarding the design of a power ultrasonic transducer with flat rectangular plate," in *COMSOL Conference, Rotterdam*, 2017.
- R. R. Andrés, E. Riera, A. Guinot, I. Martínez, and A. Pinto, "Coherent sound field generated by an airborne power ultrasonic transducer with rectangular plate radiator for food dehydration purposes," in *UIA Symposium, Dresde (Germany)*, 2017.
- R. R. Andrés, E. Riera, and A. Pinto, "Study about the influence of the shape of a horn in the mechanical behavior of an airborne power ultrasonic transducer with rectangular radiator," in *UIA Symposium, Dresde (Germany)*, 2017.
- R. R. Andrés, V. M. Acosta, A. Pinto, and E. Riera, "Airborne power ultrasonic systems for food dehydration processes intensification," in *25th International Congress on Sound and Vibration ICSV25, Hiroshima (Japan)*, 2018.
- R. R. Andrés, J. A. Cárcel, and E. Riera, "New ultrasonically assisted drier for atmospheric freeze-drying processes," in *XI Congreso Iberoamericano de Acústica FIA 2018, Cádiz (Spain)*, 2018.
- R. R. Andrés and E. Riera, "Optimization of the acoustic pressure distribution inside a freeze-drying chamber," in *COMSOL Conference, Cambridge*, 2019.

H.5- Contributions in national conferences and symposiums.

- R. R. Andrés, A. Blanco, E. Riera, V. M. Acosta, I. Martínez, A. Pinto, et al., "Sistema de control y caracterización de transductores ultrasónicos de potencia (UdP) basado en software Labview," in Tecniacústica, Valencia, 2015.
- R. R. Andrés, V. M. Acosta, and E. Riera, "Ultrasonic field generated by different airborne power ultrasonic transducers with extensive radiators," in Tecniacústica 2017 A Coruña 3-6 Octubre 2017, pp. 1299-1312.

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