LICOR - Liquid Columns' Resonances

WL-FPM-LICOR

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Abstract

The aim of the experiment LICOR was the investigation of the axial resonances of cylindrical liquid columns supported by equal circular coaxial disks. In preparation of the D-2 experiment a theoretical model has been developed, which exactly describes the small amplitude oscillations of finite cylindrical columns between coaxial circular disks. In addition, in terrestrial experiments the resonance frequencies of small liquid columns with up to 5 mm in diameter have been determined and investigations with density-matched liquids (silicon oil in a water/methanol mixture) have been performed. For the D-2 experiment LICOR the front disk and the rear disk for use in the AFPM have been constructed and equipped with pressure sensors and the necessary electronics. The pressure exerted by the oscillating liquid column on the supporting disks was as low as 10 Pa. Since the data downlink of the Materials Research Laboratory was just one signal per second and channel, it was necessary to determine amplitude and phase of the pressure already in the LICOR disks. The D-2 experiment has been successfully performed. It has fully confirmed the theoretical models and remarkably supplements the experiments on small liquid columns and on density-matched columns.

Introduction

It was the aim of the D-2 experiment LICOR to achieve a consistent understanding of the axial oscillations of cylindrical liquid columns supported by coaxial circular disks. Configurations of this type occur in the floating zone method of crystal growth. Of special interest are the frequencies of the resonances, where at the nth resonance n nodes of the surface deflection are observed. The first resonance frequency approaches zero, if by increasing its length the column reaches its stability limit. For resonance detection three different methods have been applied, namely visual observation, monitoring the pressure on the vibrating supporting disks and image processing of the video recordings.

The D-2 experiment LICOR has been based on four supplementary methods, see Fig. 1. A nearly cylindrical column between circular disks requires a low Bond number

$$B = \frac{g\,\Delta\rho\,R^2}{\sigma} \qquad (1)$$

where R is the column radius, g the acceleration due to gravity, $\Delta\rho$ the density difference between the fluid of the column and the surrounding medium, and σ the surface tension of the fluid under consideration.

In an experiment a low Bond number may be achieved by

- investigations on small liquid columns (R^2 small)

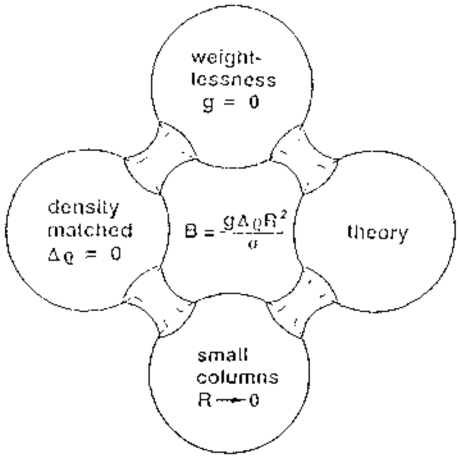


Fig. 1: The four supplementary methods for studying the behaviour of liquid columns with low Bond number.

- investigations with density adjusted liquids ($\Delta\rho$ small)
- experiments in low gravity conditions (g small).

Theory

The resonance frequencies of liquid columns are determined by the balance between the kinetic energy of the liquid motion and the potential energy of the resultant surface deformation. This means that the resonance frequencies are properly scaled by

$$\frac{\text{kinetic energy}}{\text{surface energy}} = \frac{\rho R^2 L (\omega R)^2}{\sigma R L} = \frac{\rho \omega^2 R^3}{\sigma} \qquad (2)$$

The sharpness of the resonance frequencies is determined by the liquid viscosity. It is properly scaled by the ratio of the transient time $^{\eta R}/_{\sigma}$ of liquid motions due to surface deformations over their damping time $^{R^2}/_{\nu}$. This dimensionless number

$$C = \frac{^{\eta R}/_{\sigma}}{^{R^2}/_{\nu}} = \frac{\rho \nu^2}{\sigma R} \qquad (3)$$

or else its square root are denoted as Ohnesorge number, capillary number or modified Reynolds number. ρ and ν are the density and the kinematic viscosity, $\eta = \rho \nu$ is the dynamic viscosity of the liquid considered.

The three scientific teams involved in LICOR have developed different theoretical models which yield slightly different resonance frequencies in agreement with the different simplifications made.

The Madrid team has investigated two different one-dimensional models, both of which are applicable to slender liquid columns and low frequencies [1 - 4]. In the one-dimensional slice model only the contribution of the axial liquid motion to the kinetic energy is taken into account. The radial contribution is disregarded. The liquid motion through each radial cross-section is obtained from the change of the liquid volumes on both sides. This lower estimate to the kinetic energy gives rise to too high resonance frequencies. The neglection of the radial motion is the more critical, the shorter the considered liquid column is. An upper bound to the kinetic energy is obtained, if one takes the axial flow for granted and calculates the radial flow from the continuity equation. In consequence of this treatment too low resonance frequencies arise, in particular for oscillations exhibiting several nodes. This applies to the Cosserat model.

The model developed by the München team [5 - 7] treats the oscillations of infinite liquid columns. Among these it selects those which satisfy the correct boundary conditions on the flow velocity at the periphery of the supporting disks. The corresponding boundary conditions at smaller radii are disregarded. With the flow velocity being less restricted in that model than in the experiment, too low resonance frequencies are obtained.

The model developed by the Frankfurt team [8 - 10] is principally exact. The only limitation is the linearization of the basic equations which is correct for small amplitude oscillations. It is based on the following steps:

- The solutions of the momentum equation plus the continuity equation in cylindrical coordinates are determined.
- There are three independent sets of solutions in terms of cylindrical Bessel functions with respect to the radius times ex-

ponential functions $\exp(im\varphi + iqz)$ in the azimuth φ and in the radial coordinate z.

- These solutions are used for satisfying the boundary conditions on the radial component and the two tangential components of the stress tensor along the surface of an infinite liquid column.
- Satisfying three boundary conditions by means of three linearly independent solutions renders a 3x3 secular determinant.
- The solutions of this secular determinant for real axial wavenumber q and complex frequency ω are the natural frequencies of inifinitely long columns.
- Instead of these natural oscillations the enforced oscillations for real frequences complex axial wavenumber q are determined.
- These are axially increasing or decreasing oscillations of the liquid column.
- From the increasing or decreasing oscillations linear superpositions are formed, which satisfy the boundary conditions on the flow velocity along the supporting disks.
- Satisfying the boundary conditions at any position across the disks would require taking into account an infinite set of solutions.
- Meeting the boundary conditions therefore is reduced to N radii on the supporting disks, which requires $2N$ solutions.
- Taking into account $N=12$ such radii reduces the error to less than two percent even without optimizing their spacing.

Among the most important results of this procedure let us mention:

- The surface shape resulting at low frequencies is that unduloid, which fits with respect to length and to volume.
- The pressure on the supporting disks is proportional to the amplitude of the excitation and is conveniently scaled by $pR^2/a\sigma$.
- Resonant oscillations arise if the axially decreasing waves reach the opposite disks and are reflected with adequate phase.
- The latter requirement generally is satisfied by the first two pairs of solutions only, such that the resonance frequencies basically follow from these solutions.
- The first resonance frequency approaches zero when the length L of the column reaches its circumference $2\pi R$ (Rayleigh instability).
- The height of the pressure maxima at the resonance frequencies varies proportional to $\sqrt{\rho\nu^2/\sigma R}$.
- The sharpness of the resonances decreases with increasing number n of nodes, i.e. only a finite number of resonance frequencies can be found experimentally.
- Decreasing $\rho\nu^2/\sigma R$ by one order of magnitude enables detection of two or three further resonances.
- At high frequencies surface waves arise, i.e. the liquid motion along the axis vanishes.

Figs. 2 and 3 show the pressure on the vibrating disk in dependence on frequency and the flow profile of the second resonant oscillation according to the calculations.

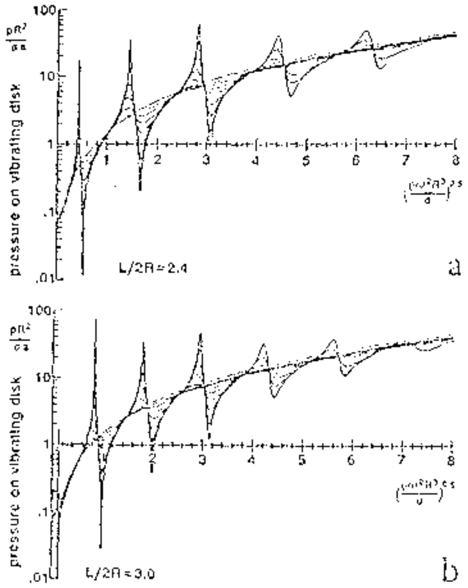


Fig. 2: The amplitude of the pressure $pR^2/a\sigma$ at the vibrating disk versus the reduced frequency $\sqrt{\rho\omega^2 R^3/\sigma}$ for varying damping parameter $\rho\nu^2/\sigma R$.
a) $L/2R = 2.4$; b) $L/2R = 3.0$.

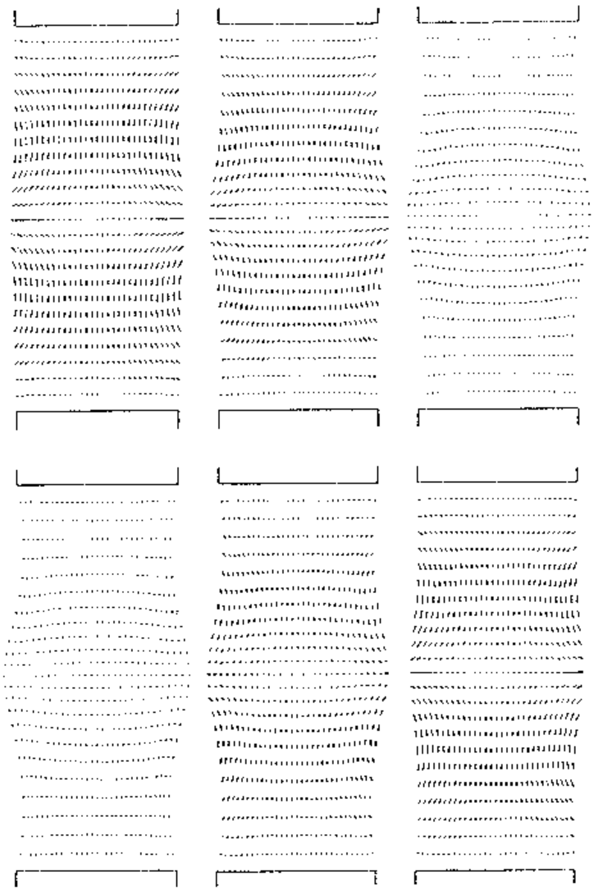


Fig. 3: The flow pattern of the second resonant oscillation in a column with aspect ratio $L/2R = 2.4$ and the damping parameter $\rho \nu^2/\sigma R = 10^{-4}$.

Small Liquid Columns

In preparation of the D-2 experiment LICOR the resonance frequencies of small liquid columns have been investigated [11]. For that aim the apparatus shown in Fig. 4 has been developed. The small columns have been established between disks made from stainless steel with 3 mm, 4 mm and 5 mm in diameter. The upper disk can be positioned in three directions by means of micrometer screws. The lower disk was electrodynamically excited. Typical amplitudes at frequencies between 15 Hz and 150 Hz ranged from $a = 2$ µm to $a = 5$ µm. The frequencies can be set manually or else a frequency ramp of variable rate may be applied.

The oscillations were observed by means of a telemicroscope and were video recorded. By using stroboscopic illumination a resting picture could be achieved at any phase. Applying a slow phase variation resulted in a slow motion picture. This is of particular importance at high frequencies, where the oscillations become non-linear.

For quantitative detection of the resonance frequencies the pressure of the liquid column on the supporting disks has been measured. The nominal sensity of the pressure sensors was 15 µV/Pa. For calibration of the pressure sensors the gas volume in a 1 liter bottle has been varied by 50 mm^2 by means of a motor driven microsyringe. The liquids used in the experiments were water and a water/glycerol mixture (Table 1).

With both liquids systematic measurements with disks of 5 mm in diameter and a frequency ramp from 15 Hz to 150 Hz were performed. The rise in frequency was 1 Hz per second. The aspect ratio $\Lambda = L/2R$ was systematically varied from 0.8 to 1.1. Fig. 5 depicts the first two resonance frequencies of a water column with 5 mm in diameter and 3.5 mm in height. Fig. 6 shows the resonance frequencies versus the aspect ratio. The resonance frequencies obtained with water (x) are somewhat lower than those obtained with the water/glycerol mixture (+). This contradicts theory, since for the mixture the Bond number and also the Ohnesorge number is slightly higher, which suggests slightly lower resonance frequencies. The full lines in Fig. 6 give the resonance frequencies according to the exact theory, the dashed lines those according to the Cosserat model. The measured resonance frequencies agree excellently with the exact model.

liquid	$\rho/\mathrm{g\,cm^{-3}}$	$\eta/\mathrm{cm^{-1}\,g\,s^{-1}}$	$\sigma/\mathrm{m\,Nm^{-1}}$	$B\,(2R = 5\,mm)$	$(l/2R)_{max}$
water	1.00	0.01	50.3	1,22	1,43
water/glycerol 25 %	1.06	0.021	48.5	1,34	1,38

Table 1: Physical data of the liquids used in terrestrial experiments on small columns.

Plateau Simulation

Plateau simulation, i. e. the use of density adjusted liquids, often is disqualified by the argument that the exterior fluid must also oscillate, such that no clear comparison with theory is possible. In addition to the density and the viscosity of the outer liquid bath, the shape of the container used and of the leads to the supporting disks have to be taken into account. An exact calculation of the resonance frequencies therefore is possible by numerical methods only. On the other hand, considering that the viscosity strongly affects the sharpness of the resonance frequencies, but only slightly their position, it should be possible to obtain useful results also by means of Plateau simulation.

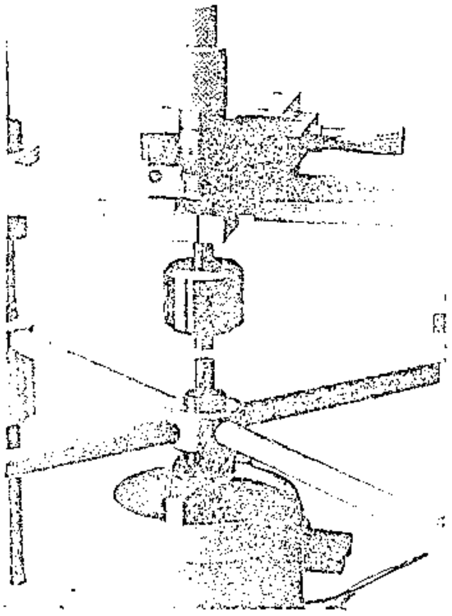


Fig. 4: The device used for investigating the resonance frequencies of small liquid columns.

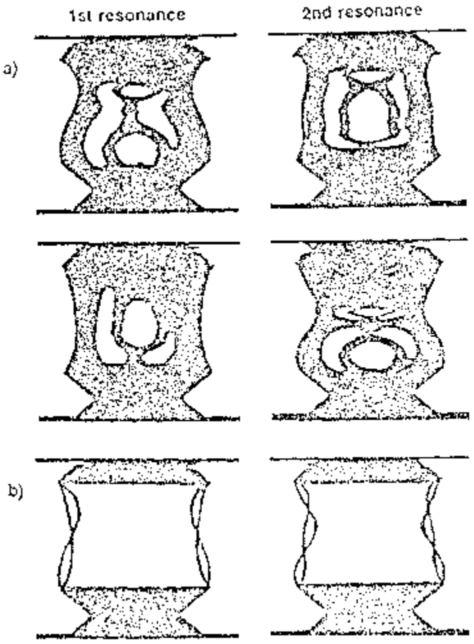


Fig. 5: The 1st and 2nd resonant oscillations of a water column with 5 mm in diameter and 3.5 mm in length.
a) Stroboscopic pictures of the extreme deformations;
b) Superposition of the silhouettes of the extreme deformations.

Plateau simulation has been used in order to familiarize science astronauts and experimenters with the behaviour of liquid columns and in particular with the detection of resonance frequencies. In the COLUMBUS mockup at ESTEC a Plateau tank is available, in which a column of silicon oil (density 0.9 g/cm) was established in a bath of water and methanol (densities 1.0 g/cm and 0.76 g/cm).

length / mm	29.8	40.3	53.4	70.0
amplitude / mm	2.0	2.0	2.0	3.0
resonance frequency / Hz				
1	0.90	0.50	0.30	0.24
2	1.96	1.22	0.72	0.48
3	3.10	2.06	1.26	0.76
4		3.02	1.90	1.20
5		> 4.00	2.68	1.68
6			3.52	2.20

Table 2: The resonance frequencies of a cylindrical liquid column with 30 mm in diameter as determined in the Plateau tank in the COLUMBUS mockup. Liquid column: silicon oil; Liquid bath: water + methanol.

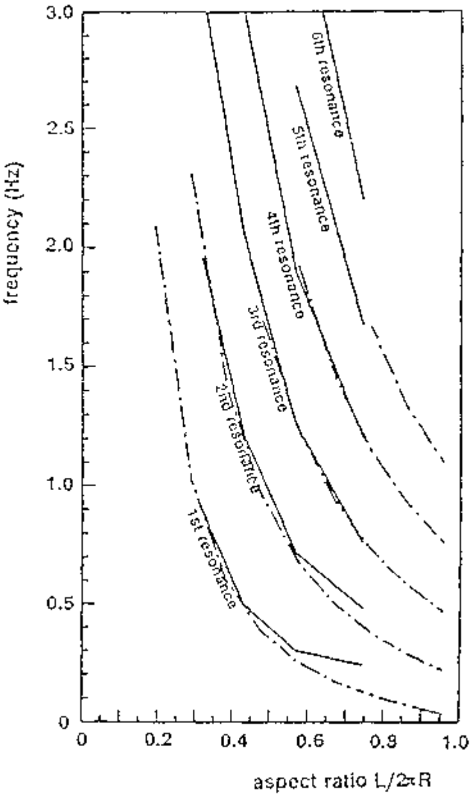


Fig. 6: Comparison of the resonance frequencies obtained in the Plateau tank with the exact theoretical model. Scaling of the frequency has been chosen according to the best fit. Solid lines: experiment; dash-dotted lines: theory.

This Plateau tank has been provided by the Madrid team, which has a long experience with this technique. After the first training with the science astronauts, a frequency ramp from 0 Hz to 5 Hz with a frequency rise by 1 Hz within 90 s has been added. This proved particularly useful during the second training performed.

By repeatedly studying the video recordings, i. e. after some visual practice, the resonance frequencies may be determined up to 0.02 Hz. With four columns with diameter 30 mm and different aspect ratio the resonance frequencies shown in Tab. 2 have been obtained.

Plotting the resonance frequencies versus the aspect ratio renders Fig. 6. Scaling of the ordinate has been chosen such that optimum fitting of the theoretical results is achieved. The good agreement of the experimental with the theoretical curves reveals that the resonance frequencies in the Plateau tank show similar behaviour as those of free liquid columns. The only adapted parameter is the frequency scaling.

Design and Performance of the LICOR Disks

The D-2 experiment LICOR has been performed in the Advanced Fluid Physics Module, AFPM, which was part of the Materials Research Laboratory. For measuring and processing the pressure of the oscillating column the special disks (front disks and rear disks)

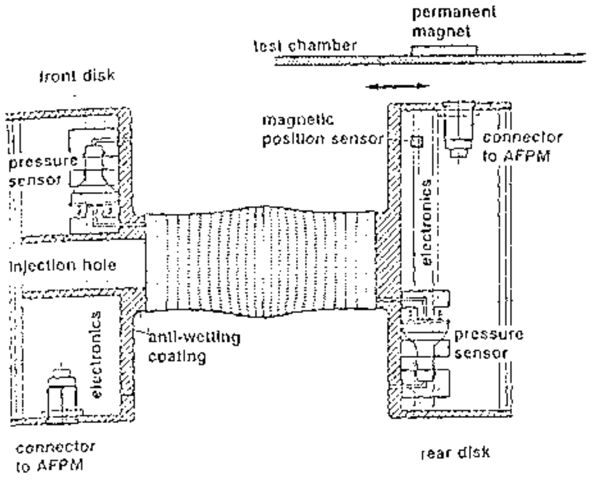


Fig. 7: The front disk and the rear disk developed for implementation in the AFPM. The hole for liquid injection is in the front disk. The rear disk is exited to vibrations. The built-in electronics evaluates the pressure amplitude and phase.

shown in Fig. 7 have been designed. The hole for liquid injection is in the centre of the front disk. The rear disk can be vibrated. Since the data transmission rate from the Materials Research Laboratory to ground was as low as 1 Hz, the signals of the pressure sensors were transformed into amplitude and phase already in the disks. The phase was counted relative to the vibration of the rear disk. In order to increase the data rate to 4 Hz, each of the amplitude and phase signals from the front disk and from the rear disk was distributed to four different channels with a time shift of 1/4 s. The channels originally were designed to serve the transmission of sixteen temperature signals. After transmission to ground the data were rearranged accordingly.

The data processing in the disks evaluates pressure signals from 0.5 Pa to 10 Pa in the frequency range from 1 Hz to 5 Hz. In that way it was possible to transmit to ground

- the amplitude of the pressure at the front disk
- the phase of the pressure at the front disk
- the amplitude of the pressure at the rear disk
- the phase of the pressure at the rear disk

at a rate of 4 Hz and with an accuracy of 16 bit.

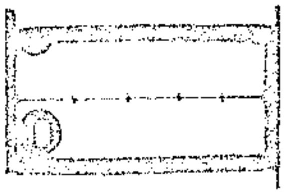
Run 1 of LICOR

The experiment LICOR was scheduled in the D-2 timeline from MET 1/23:18 to MET 2/02:50 (MET = Mission Elapsed Time). It has been placed in such a way that during the essential steps (the frequency ramps) Real Time TV was available. LICOR has been performed by PS-1, Dr. Ulrich Walter.

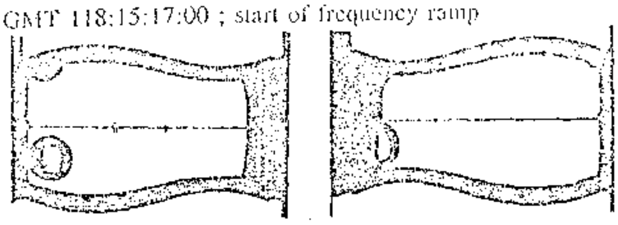
LICOR was the second experiment to run in the AFPM following the experiment STACO. Due to several delays during preparation of the AFPM, the latter experiment had suffered by severe time constraints. Due to that experience, staying within the given time frame was strongly watched during the LICOR performance. It was essential that the intended frequency ramps from 0 Hz to 5 Hz, each lasting 7:30 min, could be observed, recorded and processed in RT-TV. The video signal was transmitted via ITALSAT to MARS Center, Napoli, to be image processed and was returned on-line.

First a column from 10 cSt silicon oil with 30 mm in diameter and nominally 47.4 mm in length was created. PS-1 started the frequency ramp at MET 2/00:27:00 (= GMT 118/15:17:00). In addition to the video signal of the oscillating columns the pressure data were received on ground. The amplitude of the pressure on the vibrating disk was plotted on one of the monitors at GSOC and excellently agreed with the precalculated curve. The pressure maxima, i.e. the resonance frequencies, could be easily identified from these data. This was much more than PS-1 and all other observers of LICOR could realize, who saw the video picture of the oscillating column only, see Fig. 8.

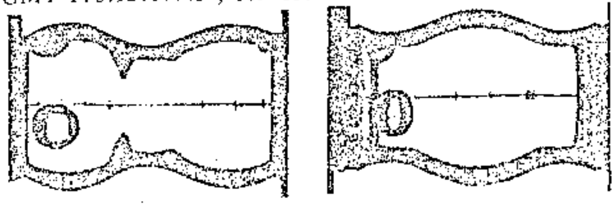
The liquid column contained unintended bubbles, which due to the obvious time constraints were not removed. The bubbles did not disturb the pressure and frequency measurements. They generally tried to avoid the



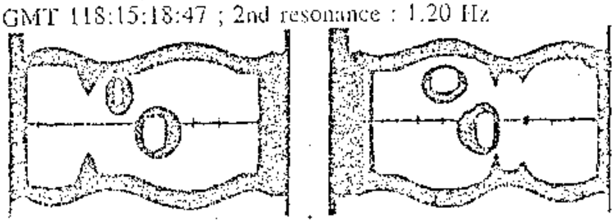
GMT 118:15:17:00 ; start of frequency ramp



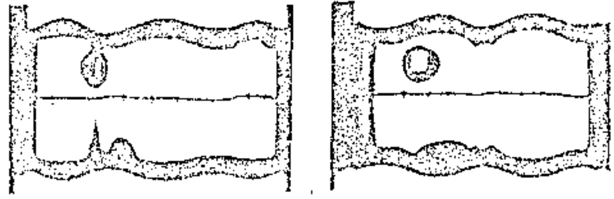
GMT 118:15:17:43 ; 1st resonance : 0.53 Hz



GMT 118:15:18:47 ; 2nd resonance : 1.20 Hz



GMT 118:15:20:03 ; 3rd resonance : 2.13 Hz



GMT 118:15:22:06 ; 4th resonance : 3.12 Hz

GMT 118:15:23:28 ; 5th resonance : 4.28 Hz

Fig. 8: The first five resonant oscillations of the column of silicon oil with 30 mm in diameter and 49.1 mm in length.

regions with high flow velocity and rather moved to the flow minima.

After application of the frequency ramp, several frequencies close to the resonances noted by the PS and the PI were set manually in steps of .04 Hz and the respective oscillations were observed in detail.

Subsequently, the length of the column was reduced to nominally 40 mm and the frequency ramp and the manual settings were repeated. As before, everything worked very well and good agreement with theory was obtained. Due to an agreement of the PIs an axial line with equidistant radial ticks had been placed between the background illumination and the liquid column. It gave valuable additional information. The start of the frequency ramp can be seen from the motion of the ticks much earlier than from the surface deformation. Residual accelerations can be clearly observed, which not at all were detected by the Microgravity Measurement Assembly, MMA. Non-axisymmetric surface deformations could be easily identified.

Fig. 9 shows the amplitude of the pressure on the vibrating rear disk and on the resting front disk during application of the frequency ramp to the first column with a nominal length of 47.4 mm (actual 49.1 mm). The full lines give the theoretical pressure according to the Cosserat model, the dash-dotted lines the pressure according to the exact theory. We find excellent agreement between the latter and the experimental values. Fig. 10 shows the phase of the pressure on the vibrating and on the resting disk during the same frequency ramp. Agreement between experiment and theory again is very good.

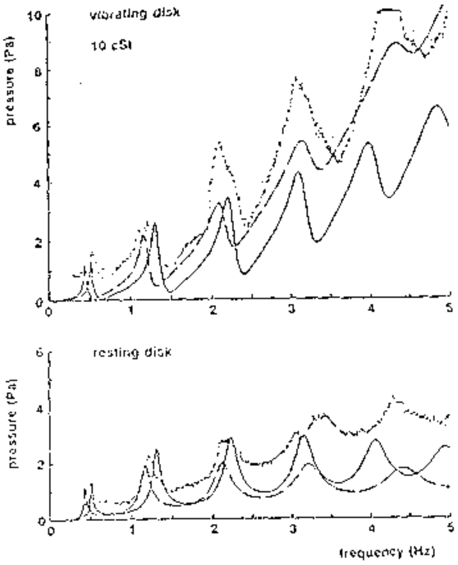


Fig. 9: The amplitude of pressure at the vibrating disk (a) and at the resting disk (b) during the frequency ramp applied to the column of 49.1 mm in length; solid lines: Cosserat model; dash-dotted lines: exact model.

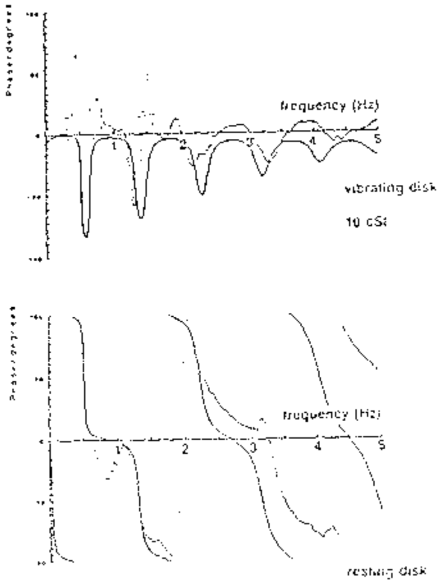


Fig. 10: The phase of pressure at the vibrating disk (a) and at the resting disk (b) during the frequency ramp applied to the column of 49.1 mm in length; solid lines: Cosserat model.

Run II of LICOR

On the third day of the D-2 Mission, the AFPM had fully broken down electronically. However, after intensive simulations of the AFPM support team with the engineering model available at GSOC and a two to three hour air-to-ground repair activity, the AFPM could be reactivated by the crew. Since the Spacelab mission was extended by one day, a second run of LICOR was enabled by means of a replanning request.

In order to save crew time, Run II of LICOR was performed with the 5 cSt silicon oil used in the preceding experiment ONSET (Onset of oscillatory Marangoni flows). In order to account for the lower viscosity, the amplitude of excitation of the rear disk was reduced from 1 mm to 0.5 mm. The front disk, due to the preceding procedures, still was shifted laterally by 0.7 mm. The request to rearrange it coaxially was renounced, since this was the step were the AFPM had broken down earlier.

As in Run I, the science astronaut was Dr. Ulrich Walter. He created a liquid column with 40 mm in length and applied the frequency ramp from 0 Hz to 5 Hz. As before, sharp maxima of pressure versus frequency showed up. The first resonance frequencies could be clearly identified, see Table 3. However, after passing the third resonance frequency the oscillation became so intense that a strong lateral motion arose and the liquid spilled over the sharp edge of the rear disk. The column subsequently broke. Since no unusual accelerations were recorded by the Microgravity Measurement Assembly, the possible reasons for the spillage are

- the lateral shift of the Front Disk by 0.7 mm
- the retardation of the full development of the resonant oscillations relative to the appearence of the pressure maximum.

The resonance frequencies found in the D-2 experiment are shown in Fig. 11 together with the results from small liquid columns and the curves from theoretical modelling.

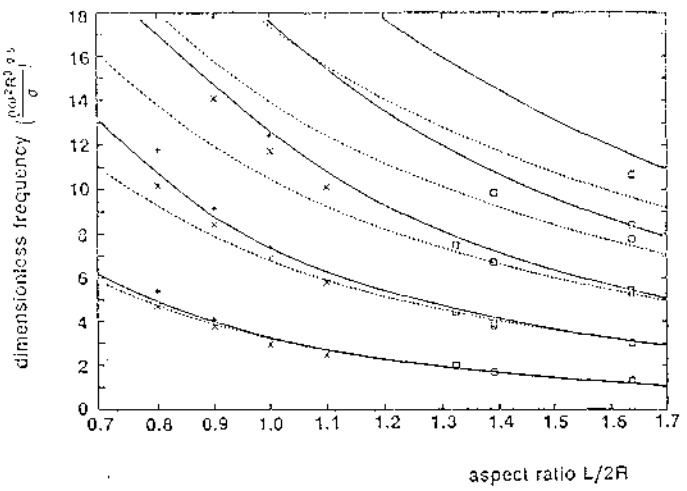


Fig. 11: The first five resonance frequencies obtained with columns of different length in the experiment LICOR together with the resonance frequencies of small liquid columns; (□) D-2 experiments; (x) small columns of water, (+) small columns of water/glycerol 25 %; solid lines: exact theory, dashed lines: Cosserat model.

Conclusions

The D-2 experiment LICOR perfectly supplements the experiments on small liquid columns and those based on density-adjusted liquids. At the same time, it has given new insight into the immediate appearence of the pressure maxima, the visual observation of resonances and the retardation of the fully developed oscillations. The automatic detection of the resonances by means of pressure sensors has proven very effective.

The unintended lateral shift of the front disk, which hasn't been corrected due to this risk of breakdown of the AFPM, has shown the sensitivity of liquid columns to non-axial perturbations. It was most likely the reason for the breakage of the column in Run II. In the subsequent re-run of the experiment STACO a column of silicon oil between circular disks with the unequal diameters 30 mm and 28 mm has been established. The column started to oscillate laterally with a period of 4.75 s and broke after about 3 min. The unequal disk diameters bring about three different surface shapes, which differ only slightly in energy. All of these surfaces are sections of unduloids. Breakage occurred after the energy of the lateral motion caused the column to switch from the unduloid with lowest energy to the one with next higher energy.

This underlines the importance of non-axial oscillations of liquid columns and of oscilla-

silicon oil	length / mm	disk	resonance frequency / Hz				
			1	2	3	4	5
10 cSt	49.1	vibrating resting video	0.53 0.53 0.48	1.20 1.21 1.20	2.13 2.19 2.04	3.12 3.38 3.40	4.28 4.30 4.31
10 cSt	41.7	vibrating resting video	0.69 0.69 0.64	1.53 1.58 1.53	2.70 2.70	3.96 3.96	 4.98
5 cSt	39.7	vibrating resting video	0.80 0.80 0.78	1.77 1.78 1.77	3.00 3.00		

Table 3: The resonance frequencies obtained from the pressure maxima and by visual evaluation of the video recordings.

tions with azimuthal wave numbers $m >= 1$. They show a much lower damping than the axial oscillations with $m = 0$.

There are good reasons to assume that the oscillatory Marangoni convection, which has been repeatedly observed in liquid columns, is coupled to capillary oscillations with $m = 1$. Marangoni convection arises, if the disks supporting the column are heated to different temperatures. A gradient in surface tension from hot to cold arises together with a surface convection in the same direction. It becomes oscillatory, if the applied temperature difference exceeds a critical value. In that case the convective flow starts to rotate azimuthally. This appears to be an oscillatory flow in a meridian light-cut. The rotating flow gives rise and in turn is supported by a corresponding surface deformation. Each investigation of oscillatory Marangoni flows therefore requires the exact knowledge of all non-axial capillary deformations.

Acknowledgements

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