

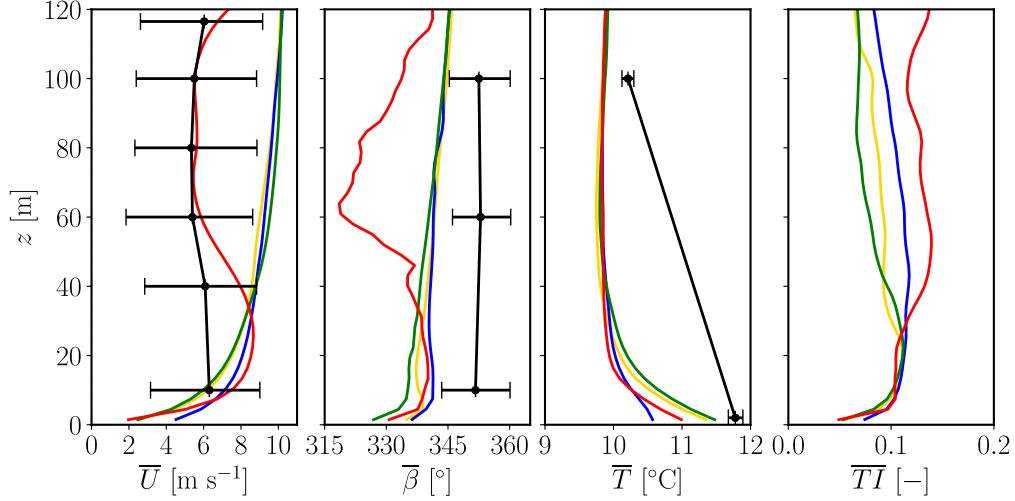


Figure 8.40: Vertical profiles of time-averaged wind speed, $\bar{U}$, wind direction, $\bar{\beta}$, and temperature, $\bar{T}$, as well as turbulence intensity, $\bar{TI}$, from numerical results corresponding to WRF-LES-d05, and experimental data from the Høvsøre mast. (—) with vertical bars correspond to experimental data with minimum and maximum values. (—) denotes the WRF-LES results at the met mast location, (—) denotes the results at a control point upstream of the wind turbine in the northwest direction (CP-inflow1), (—) stands for the results at a point one rotor diameter upstream of the wind turbine (CP-inflow2), (—) denotes the results at a control point upstream of the wind turbine in the northeast direction (CP-inflow3), and (—) denotes the model predictions at a control point in the wake of the wind turbine close to the met mast (CP-wake). The reader is referred to Figure 8.38 for the layout of the WRF-LES control points.

measurement campaign. When backing winds occur, the wind speed and wind direction profiles exhibit a backward S-shaped pattern. Nonetheless, the wind direction profile was nearly flat and no backing wind occurred during the relevant measurement period, proving the wake effects on the measured weather data. The reason why the wind direction profile in the wake of the wind turbine differs from the experimental data is probably due to the selection of the control point location. The temperature profiles show a trend commonly observed in typical unstable ABL conditions because the temperature drops with altitude as the ground is heated by the sun. The wake of the wind turbine exhibited higher turbulence levels, primarily driven by enhanced turbulence mixing resulting from strong wind shear and increased mechanical production of turbulent kinetic energy around the top-tip level [379]. Here, $\bar{TI}$ was calculated from the three velocity components and normalized by the mean wind speed at 80 m.

Figure 8.41 shows the Power Spectral Density Functions (PSDFs) of longitudinal, u , lateral, v , and vertical, w , velocity components' time series, resolved by the model at 80 m at different locations. Spectra are computed using the Welch method and by dividing 30-min time series into 15 s windows (7.5 s overlapping intervals using Hann window). A first-order low-pass Butterworth filter was applied to mitigate the aliasing effect at high

Backing wind, in meteorology, refers to the counterclockwise shift in wind direction within the Northern Hemisphere [117].

Wind velocity components are expressed in the geographic coordinate system.

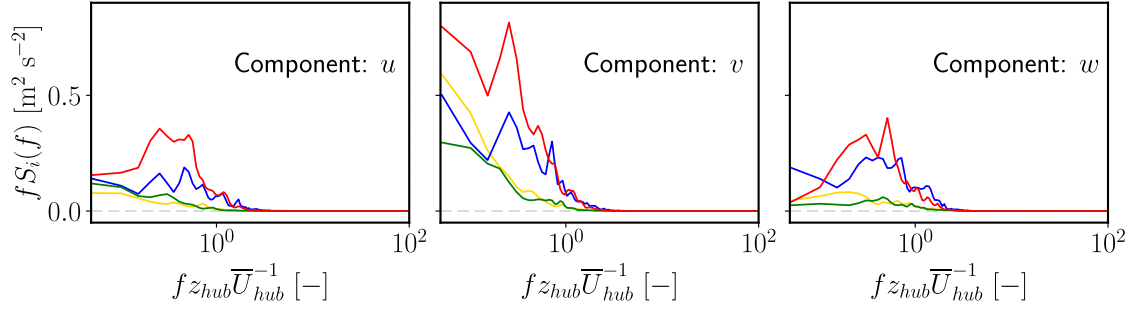


Figure 8.41: Spectra of velocity components during 30-min period, given as a function of nondimensional frequency normalized by hub height, $z_{hub} = 80$ m, and 30-min average freestream wind speed at 80 m, $\bar{U}_{hub}$. (—) denotes the WRF-LES results at the met mast location, (—) denotes the results at a control point upstream of the wind turbine in the northwest direction (CP-inflow1), (—) stands for the results at a point one rotor diameter upstream of the wind turbine (CP-inflow2), (—) denotes the results at a control point upstream of the wind turbine in the northeast direction (CP-inflow3), and (—) denotes the model predictions at a control point in the wake of the wind turbine close to the met mast (CP-wake). The reader is referred to Figure 8.38 for the layout of the WRF-LES control points.

frequencies. Since the power spectra are closely related to the variance of the time series, higher energy levels were observed at all frequencies, at those locations in the wake of the wind turbine, with the lowest energy levels at upstream locations. The results represented by the blue curves correspond to the numerical data determined at the met mast location, giving the second highest energy levels, and exhibit the partial effect of the wind turbine wakes at that location. Higher energy values were observed in the v -velocity component spectrum compared to other velocity components. This is likely because the wind blew from the north for almost the entire measurement period.

8.2.4 Part II – Wake modeling and power estimation

The SWT-2.3-93 WT has 80 m hub height and 93 m rotor diameter. It is a variable-speed and variable-pitch wind turbine. The design data of this WT is not available, thereby an approximated version of it, called the generic SWT-2.3-93 WT [54], is used in the analysis. Nacelle and tower aerodynamic effects were parameterized utilizing an approach similar to that of the WLGL model. In order to mimic a real wind turbine, blade precone and rotor shaft angles were also considered. Additional information for the generic SWT-2.3-93 WT can be found in Table 8.7.

No wind turbine speed and pitch controllers were utilized since the noise measurements of the wind turbine were performed at fixed rotational speed ($\Omega = 14$ RPM) and fixed blade

Table 8.7: Characteristics of the generic SWT-2.3-93 wind turbine [54].

Parameter	Hub height	Rotor shaft tilt	Rotor diameter	Wind turbine base elevation	Wind turbine location	Rated power	Power converter	Pitch control
Value	80 m	6°	93 m	0.3 m	56.442237°N, 8.150590°E	2.3 MW, at 16 RPM	Variable speed	Variable pitch

pitch angle ($\theta_p = -2^\circ$). A yaw control algorithm was used to yaw the wind turbine to account for changes in wind direction. The wind direction was estimated at $1D$ upstream of the WT. As discussed in Churchfield [54], the blade properties were approximated to match the manufacturer's power curve. The chord, twist, and airfoil polars, provided in the reference report, were used as input parameters for the WLGL simulations.

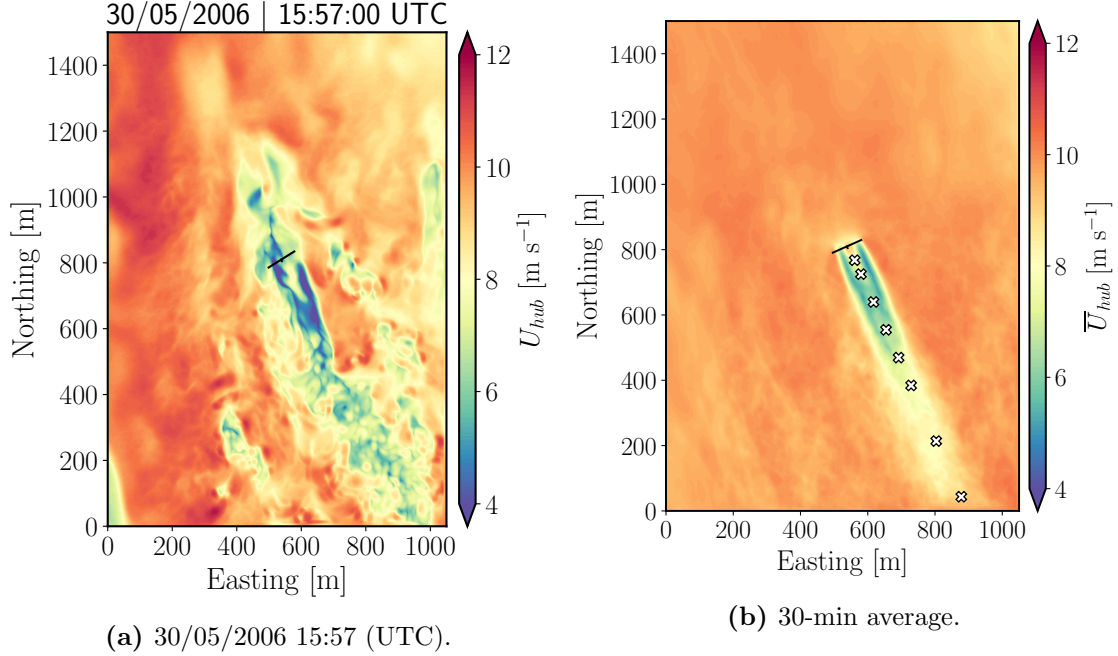


Figure 8.42: Color maps of instantaneous, U_{hub} , (a) and 30-min time-averaged (b) horizontal wind speed, $\bar{U}_{hub}$, at hub height. The solid black line represents the WT and white crosses denote the locations of the control points used for comparison of wake velocity deficit profiles shown in Figure 8.44.

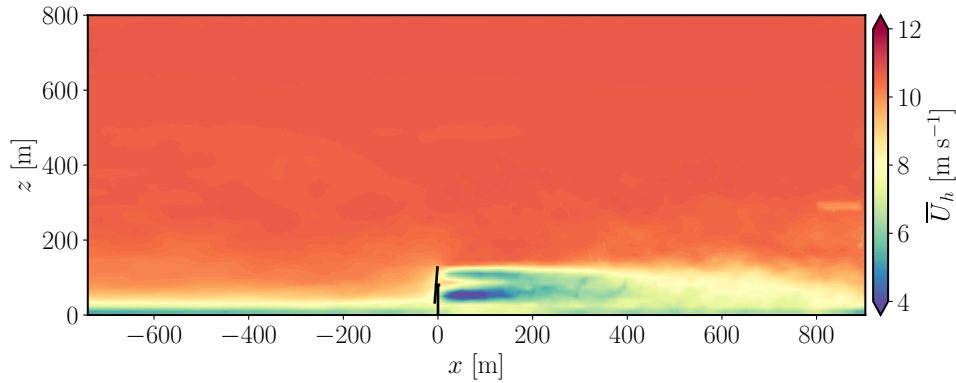


Figure 8.43: Color map of 30-min time-averaged horizontal wind velocity along the wake transect (see Figure 8.38 for details). The wind turbine is represented schematically by the solid black line.

Figure 8.42a shows a snapshot of the horizontal wind speed at hub height. In Figures 8.42b and 8.43, color maps of 30-min time-averaged horizontal wind velocity at hub height and along the wake transect are illustrated, respectively. Both figures reveal that the wake persists up to $\sim 5D$ downstream of the WT and is recovered beyond. This is an expected wake behavior in daytime conditions due to high turbulence mixing (especially a few

hours before sunset when the state of the ABL is highly unstable). The mean turbulence intensity at hub height was $\overline{TI} = 9.1\%$. The aerodynamic drag effect due to the nacelle is not visible, yet the tower adds extra aerodynamic drag to the wake below hub height, because the diameter of the tower is nearly twice the grid size. Another reason for the formation of a larger velocity deficit region below hub height is due to lower wind speeds near the ground.

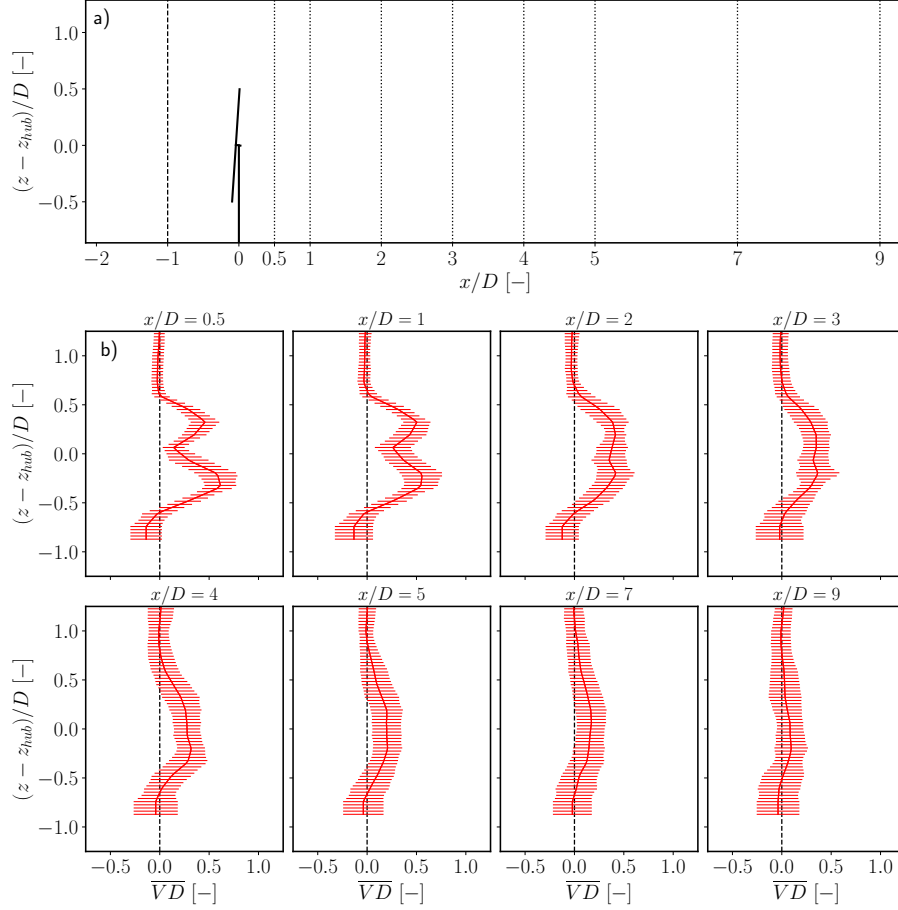


Figure 8.44: (a) Locations of the corresponding mean wake velocity deficit ($\overline{VD}$) profiles shown below, as a function of nondimensional height, with z_{hub} and D being the hub height and rotor diameter, respectively. The dashed black line indicates the inflow location, whereas the black dotted lines represent different locations downstream of the wind turbine (a). 30-min average wake velocity deficit profiles obtained from WLGL simulation at different downstream locations of the wind turbine (b). Red horizontal lines cover the mean $\pm$ standard deviations of velocity deficits during the 30-min time averaging period of the simulation results.

Figure 8.44 shows the time-averaged wake velocity deficit profiles at different locations downstream of the wind turbine, from $x/D = 0.5$ to $x/D = 9$. The aerodynamic effect of the tower is more clear in vertical $\overline{VD}$ profiles, as the tower induces an evident wake up to $x/D = 2$. Beyond that, no significant tower aerodynamic effect is discernible.

Time series of power, P , thrust, T , rotational speed, Ω , and pitch angle, θ_p , of the generic SWT-2.3-93 wind turbine represented by the WLGL model are illustrated in Figure 8.45.

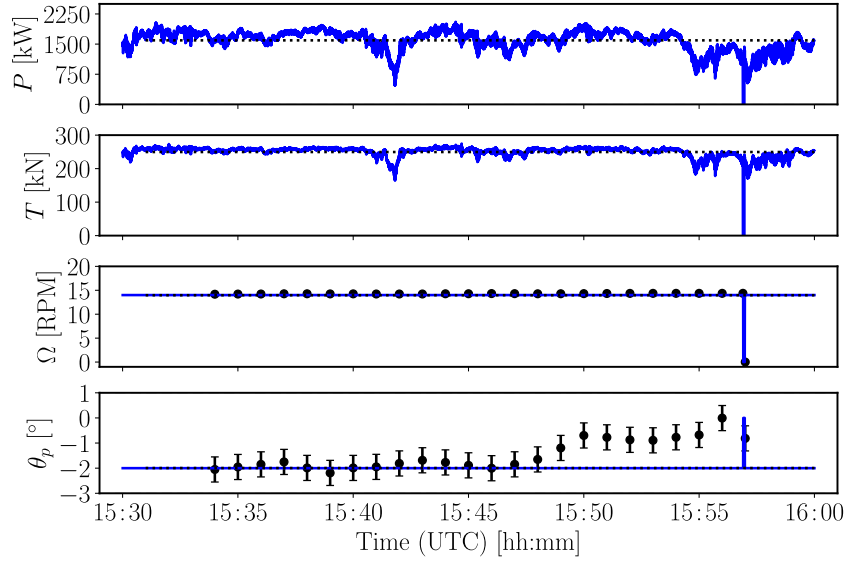


Figure 8.45: Time series of power, P , thrust, T , rotational speed, Ω , and pitch angle, θ_p , of the generic SWT-2.3-93 wind turbine represented by the WLGL model. (—) corresponds to the WLGL model estimations for aerodynamic power and thrust, and pitch angle. (---) denotes the mean values over the period of interest. (—) indicates experimental data reproduced from Leloudas [183].

Since there is no power and thrust measurements, numerical estimations are provided solely. During the period of interest, wind turbine power output and thrust did not change significantly, except for some short intervals roughly between 15:41:15:42 and 15:55-16:00 (UTC). The main reason for this was sudden changes in wind direction. The WT needs some time to align the rotor with the incoming wind direction; therefore, the time required to properly yaw the WT, may take longer than the duration of the sudden change in wind direction. This reduces the power production, and thus the overall efficiency of the WT. Furthermore, the WT can stop when the incoming wind speed is lower than the cut-in wind speed of the WT ($V_0 < V_{\text{cut-in}} = 4 \text{ m s}^{-1}$), which ensued for a short period between 15:56:54-15:56:58 (UTC). The slowdown in wind speed, as depicted in Figure 8.42a, is the main reason why the wind turbine stopped for a short time in the WLGL simulation. No aerodynamic force is calculated if the wind turbine is stopped. Note that there is neither experimental data for wind turbine aerodynamic response to compare, nor any evidence that the wind turbine was intentionally shut down at around 15:57 (UTC). The estimated mean aerodynamic power output and thrust are 1597 kW and 250.2 kN, respectively.

8.2.5 Part III – Aeroacoustic noise modeling

One of the primary sources of noise from modern wind turbines is trailing-edge (TE) noise [245, 342]. It is caused by the scattering of the turbulent boundary layer passing over a sharp edge, which is the trailing edge of wind turbine blades. It is broadband and generally dominates the overall noise level emitted by wind turbine blades. In addition, the trailing-edge noise highly depends on the geometric shape of the airfoils, and unsteady and non-uniform values of the incoming wind velocity and local angle of attack. The

basics of wind turbine aeroacoustics and relevant numerical methodologies used in noise modeling throughout this dissertation have already been presented in Sections 4.2 and 5.3.

The aim of this section is to predict a real-scale wind turbine noise by making use of the WLGL model estimates of aerodynamic quantities, such as the angle of attack and flow velocity relative to the blade sections (or the chord Reynolds number), which are determined at the locations of the blade elements distributed along the blade. Due to the fact that the WLGL model allows the positions of the blades to be tracked at each time step, the time series of such aerodynamic quantities can be obtained. Using the high-frequency outputs of the WLGL model, the instantaneous values of all necessary variables to be used as inputs in noise modeling of the full-size SWT-2.3-93 WT can be determined. The WLGL model provides direct inputs for the RANS modeling of the NACA63(3)218 airfoil from which the outer part of the blade ($r/R \geq 0.72$) is made. Since higher levels of TE noise are encountered in the outboard of the blade, due to higher relative velocities seen by the blades, only the last 30% of the blade has been considered in this work.

This section is organized as follows: a brief description of the numerical set-up of the RANS simulations is given first. Next, a verification analysis for the RANS simulation of the isolated NACA0012 airfoil, including a mesh independence analysis is presented. Due to the unavailability of the experimental and numerical data for the NACA63(3)218 airfoil, the NACA0012 profile has been chosen in order to determine the optimum mesh configuration and the appropriate wall-pressure spectrum model required for the Amiet's model for trailing-edge noise. Finally, after all the required parameters have been determined, the trailing-edge noise of the full-size SWT-2.3-93 is analyzed. The results are then compared with the available experimental data. Conclusions are drawn at the end of the section.

2D RANS modeling of isolated NACA 0012 and NACA 63(3)218 airfoils

2D RANS computations of isolated NACA 0012 and NACA63(3)218 airfoils were performed using the steady RANS solver of STAR-CCM+, with the Shear-Stress-Transport (SST) $k_t\text{-}\omega_t$ turbulence model [213]. The $k_t\text{-}\omega_t$ SST model was chosen due to the model's higher accuracy in modeling separated flows, flows with high-pressure gradients, and turbulent flow over curved geometries, such as airfoils [276].

A JAVA macro file was used to automate the entire process, from the generation of the airfoil geometry and mesh, through CFD analysis and data output. The mesh comprises 25 structured inflation layers around the airfoil and polygonal cells in the background mesh. The thickness of the first layer, Δy_1 , was determined using the classical definition of dimensionless distance from the wall, y^+ , following Equation (5.124).

Dirichlet boundary conditions (BCs) for all variables were specified at the inlet boundary, with zero gradient BC for pressure, p . Low Reynolds number wall functions were used on the airfoil surface for kinetic energy, k , turbulent viscosity, ν_t , and specific dissipation rate, ω_t . A no-slip condition was applied for the longitudinal velocity, u , and the pressure

gradient was set to zero, $\nabla p = 0$. At the outlet, the gradients of all variables were set to zero, (i.e., $\nabla f = 0$, with f being the quantity of interest), except for the pressure, which was set to zero ($p = 0$) (gauge pressure). The inlet BCs for k_t and ω_t were defined as a function of the freestream velocity, U_∞ , turbulent intensity, TI , and the mixing length scale, ℓ , as given in Equations (5.126a) and (5.126b). The initial value of turbulent viscosity, ν_t , was determined from Equation (5.127). More details on the RANS modeling can be found in Section 5.3.1.

For the convergence criterion of the simulations, a stopping rule based on the asymptotic behavior of the monitored values was used. The simulation stops when the monitored values (e.g., residuals of continuity, x -momentum, y -momentum, k_t , and ω_t equations) are stabilized within a certain range over several iterations (e.g., 1000 iterations). If the selected criterion is not met, the simulation stops at the user-defined maximum number of iteration steps, which was set to 50000 in this work.

It is important to note that, for both airfoils, the RANS calculations are based on dimensional velocity, kinematic viscosity, chord, and so on; both for mesh independence study and isolated airfoil noise estimation. On the other hand, these quantities were made dimensionless for 2D RANS calculations of the NACA 63(3)218 airfoil to be used as input in noise modeling of the full-size wind turbine. After all RANS calculations were completed and the necessary boundary layer parameters were found for the relevant flow conditions, these dimensionless quantities were converted to dimensional form by rescaling according to the local chord length and relative velocity. Such a methodology based on bilinear interpolation is required to estimate unknown values that lie between known values of boundary layer parameters calculated from RANS simulations. This reduces the number of RANS simulations required to determine boundary layer parameters for the angle of attack, α , and chord Reynolds number, Re_c , obtained from the WLGL model. If these parameters were calculated from individual RANS simulations for each α and Re_c value, they would have always fallen within the range of known values, as expected. An error analysis of the accuracy of interpolated boundary layer parameters, with respect to a reference individual RANS simulation using the same freestream inflow input parameters ($\alpha = 7.92^\circ$, $Re_c \simeq 3258381$, $U_\infty \simeq 68.25 \text{ m s}^{-1}$, $c \simeq 0.6889 \text{ m}$ and $\rho_\infty = 1.226 \text{ kg m}^{-3}$), is given in the following sections (see Table 8.13).

Mesh independence study

The purpose of the mesh independence study in this work is to ensure that the RANS simulation results for the NACA 0012 and NACA 63(3)218 airfoils are not overly influenced by the mesh selection, and accurately represent the underlying physics of the problem. Moreover, it helps determine the appropriate level of mesh refinement required to achieve reliable results without unnecessarily high computational costs.

The RANS simulation of the flow field around an airfoil is, in principle, sufficient to provide the necessary input data for noise models, as long as the near-wall boundary layer is

Table 8.8: Some mesh metrics used for the mesh sensitivity analysis of the NACA 0012 airfoil.

Parameter	Symbol	Unit	Mesh density		
			Coarse	Medium	Fine
Number of vertices	N_{vert}	[—]	298399	322988	337555
Number of cells	N_{cell}	[—]	159139	174880	180463
Initial (or desired) value of y^+	y_{init}^+	[—]	5.0	0.9	0.2
Minimum value of y^+	y_{min}^+	[—]	0.422	0.082	0.026
Maximum value of y^+	y_{max}^+	[—]	6.610	1.115	0.235
Value of y^+ at $x/c = 0.9962$	$y_{x/c=0.9962}^+$	[—]	0.949	0.150	0.033
Normalized minimum wall distance	$\Delta y_1/c$	[—]	45.8×10^{-6}	8.0×10^{-6}	2.5×10^{-6}

resolved well enough. An objective of this work is the assessment of the accuracy and numerical robustness, depending on the near-wall resolution of the RANS model. Performing such an analysis will help establish the appropriate computational set-up required to extract turbulent boundary layer parameters to be used in the noise modeling of the selected wind turbine. Mesh independence study in this work is based on the investigation of the influence of different y^+ values on the accuracy of estimated boundary layer parameters, wall-pressure spectra, and far-field sound pressure level spectra in third-octave band because finding an optimal value of y^+ is of key importance to accurately capture turbulent boundary layer parameters at the trailing edge. For that reason, y^+ values of 5, 0.9, and 0.2 have been chosen, corresponding to coarse, medium, and fine meshes, respectively. The automatically generated mesh configurations are shown in Figure 8.46. Note that since the thickness of the first layer in the fine mesh configuration, $\Delta y_1 \simeq 1 \times 10^{-6}$ m, is about eighteen times smaller than in the coarse mesh, $\Delta y_1 \simeq 18.32 \times 10^{-6}$ m, the cell size of the surrounding mesh is larger. As the number of mesh cells used in all cases was similar, the coarser mesh surrounding the airfoil was generated due to much thinner inflation layers and denser mesh closer to the wall. The number of vertices and cells, minimum wall distances, as well as minimum and maximum values of for each mesh are given in Table 8.8.

As mentioned, due to the lack of necessary information to validate the 2D RANS results of NACA 63(3)218, only validation of NACA 0012 airfoil results was done and the conclusions were applied when determining the optimum computational set-up for the RANS modeling of NACA 63(3)218.

Airfoil configuration

NACA 0012 is a symmetrical airfoil with a maximum thickness of 12% at 30% of the chord and has a sharp trailing edge.

NACA 63(3)218 is an asymmetrical airfoil with a maximum camber and thickness of 1.1% and 18% at 24.9% and 34.9% of the chord, respectively. Like NACA0012, it also has a sharp trailing edge.

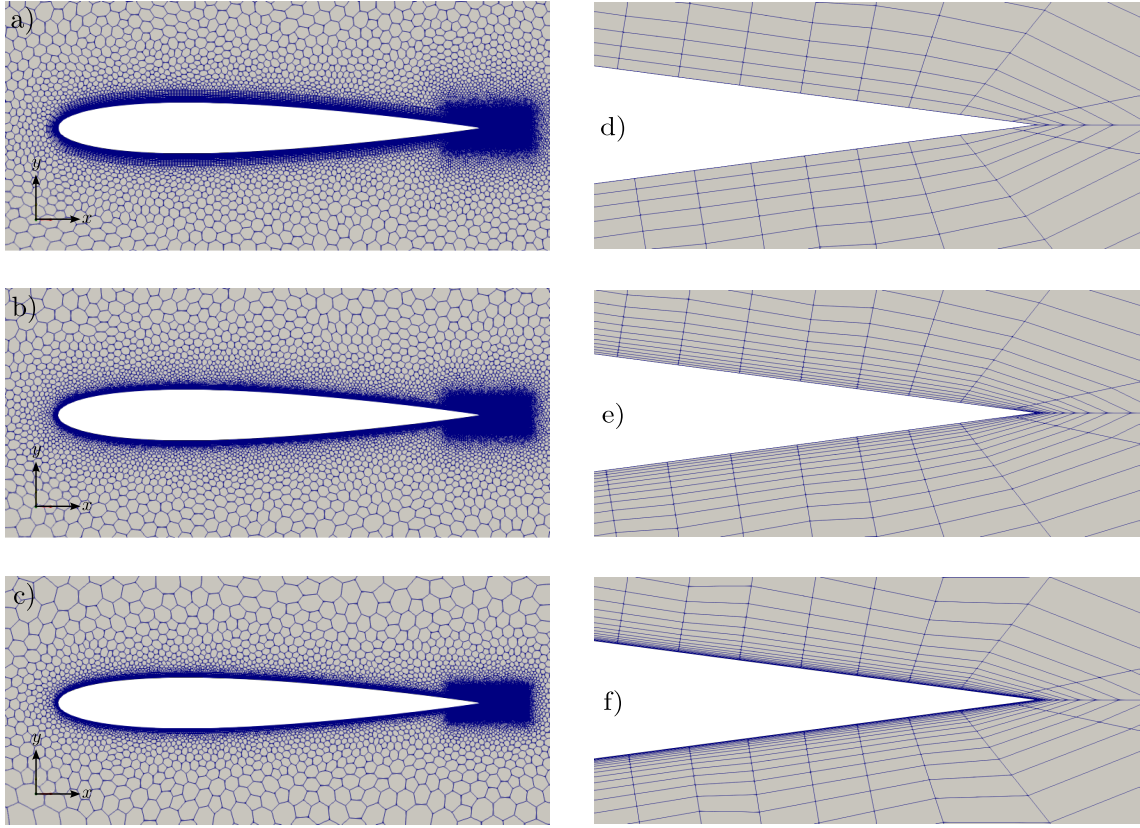


Figure 8.46: Representation of coarse (a), medium (b), and fine (c) meshes used in RANS simulations of the NACA 0012 airfoil for mesh independence analysis. The figures on the right also show a close-up view of the airfoil mesh near the trailing edge for coarse (d), medium (e), and fine (f) mesh configurations. y^+ values for coarse, medium, and fine meshes are 5, 0.9, and 0.2, respectively.

Flow conditions and domain configuration for RANS modeling

The flow around the NACA 0012 airfoil was forced with a freestream velocity of $U_\infty = 56 \text{ m s}^{-1}$, yielding a Mach number of $M_\infty = U_\infty/c_\infty = 0.1664$, with c_∞ being the speed of sound at freestream, and the freestream Reynolds number of $\text{Re}_\infty = U_\infty c/\nu = 1.5 \times 10^6$. The ambient density, temperature, and pressure were $\rho_\infty = 1.181 \text{ kg m}^{-3}$, $T_\infty = 281.4 \text{ K}$, and $p_\infty = 95429 \text{ Pa}$, respectively. For NACA 63(3)218, a freestream velocity of $U_\infty = 58.84 \text{ m s}^{-1}$ was selected to perform RANS computations, which results in a Mach number of $M_\infty = 0.1731$ and the freestream Reynolds number of $\text{Re}_\infty = 3 \times 10^6$. The ambient density, temperature, and pressure were chosen as $\rho_\infty = 1.225 \text{ kg m}^{-3}$, $T_\infty = 285.2 \text{ K}$, and $p_\infty = 101325 \text{ Pa}$, respectively. Note that the ambient conditions chosen for the RANS modeling of the NACA 63(3)218 airfoil correspond to ideal conditions, as no comparable data are available.

The computational domains, proportional to the chord length of each airfoil, extend from $L_x/c = -5$ to $L_x/c = 10$ in the longitudinal direction and from $L_y/c = -5$ to $L_y/c = 5$ in the vertical direction, where L_x and L_y are the length and height of the domain, respectively. The trailing edge of the two airfoils are located at $x/c = 1.0$ and $y/c = 0.0$.

Table 8.9: Inflow conditions and airfoil prototype dimensions for 2D RANS computations of the NACA 0012 and NACA 63(3)218 airfoils.

Parameter	Symbol	Unit	 NACA 0012	 NACA 63(3)218
Freestream velocity	U_∞	m s^{-1}	56	58.84
Speed of sound	c_∞	m s^{-1}	336.34	340
Kinematic viscosity	ν	$\text{m}^2 \text{s}^{-1}$	1.4933×10^{-5}	1.4710×10^{-5}
Air density	ρ_∞	kg m^{-3}	1.181	1.225
Temperature	T_∞	K	281.4	285.2
Pressure	P_∞	Pa	95429	101325
Reynolds number	Re_∞	$[-]$	1.5×10^6	3.0×10^6
Mach number	M_∞	$[-]$	0.1664	0.1731
Chord length	c	m	0.4	0.75
Blade span	L_s	m	1	1
Inflow turbulence intensity	TI_∞	$[-]$	0.001	0.0007
Angle of attack	α	$^\circ$	0	6, 8, 10, 12, 14, 16

Note. Inflow conditions used in RANS simulations of the NACA 0012 airfoil correspond to case #1 of the Benchmark Problems for Airframe Noise Computations II (BANC-II) Workshop [127].

Around the trailing edge of the airfoil, the mesh was refined to better capture the turbulent boundary layer. To do so, a refinement box of size $L'_x \times L'_y$, with $L'_x/c = 0.175$ and $L'_y/c = 0.07$ being the length and height of the refinement box, respectively, was added and filled with elements of size $\Delta/c = 0.0015$. The mesh refinement region around the trailing edge was aligned with the chord and centered on the trailing edge of the NACA 0012 airfoil. For the NACA 63(3)218 airfoil, the refinement box was shifted up in the normal direction perpendicular to the chord to account for the boundary layer thickening on the suction side. The trailing edge was located at a distance $y/c = 0.025$ from the bottom of the refinement box and at a distance $y/c = 0.045$ from the top. The refinement box remained centered on the trailing edge in the direction of the chord. The RANS simulations of the flow around the NACA 0012 and NACA 63(3)218 airfoils were performed at an angle of attack of $\alpha = 0^\circ$ and $\alpha = 6^\circ, 8^\circ, 10^\circ, 12^\circ, 14^\circ, 16^\circ$, respectively. A summary of the flow conditions used for both airfoils is presented in Table 8.9.

The far-field noise spectra of the two airfoils were calculated at a distance $y/c = 1$ m from an observer assumed to be in the same direction as the longitudinal incoming flow ($\theta_r = 0$). The span of the corresponding airfoil is assumed to be $L_s = 1$ m. The chord length for NACA 0012 was $c = 0.4$ m, whereas it was set to $c = 0.75$ m for the RANS modeling of NACA 63(3)218. The RANS data found in the literature for NACA 0012 have been reproduced from Herr and Kamruzzaman [127] and Küçükosman [170] for comparison. Due to the lack of experimental data in the literature for the NACA 63(3)218 airfoil, the results of current RANS simulations have been compared with the available RANS data reported in the literature.

Measurements of the NACA 0012 airfoil, including pressure distribution on both sides of the airfoil, velocity profile, wall-pressure spectra, and far-field noise, were performed in the Laminar Wind Tunnel (LWT) of the University of Stuttgart [127].

Results of the mesh sensitivity analysis for the NACA 0012 airfoil: Near wake flow, surface pressure spectra, and far-field noise

Figure 8.47 shows vertical profiles of nondimensional flow parameters in the near wake, for the NACA 0012 airfoil. These parameters are longitudinal velocity, u/U_∞ , turbulent kinetic energy, k_t/U_∞^2 , specific dissipation, $\omega_t c/U_\infty$, and turbulent length scale, Λ/c . These profiles were obtained at a position $x/c = 0.9962$ from the leading edge.

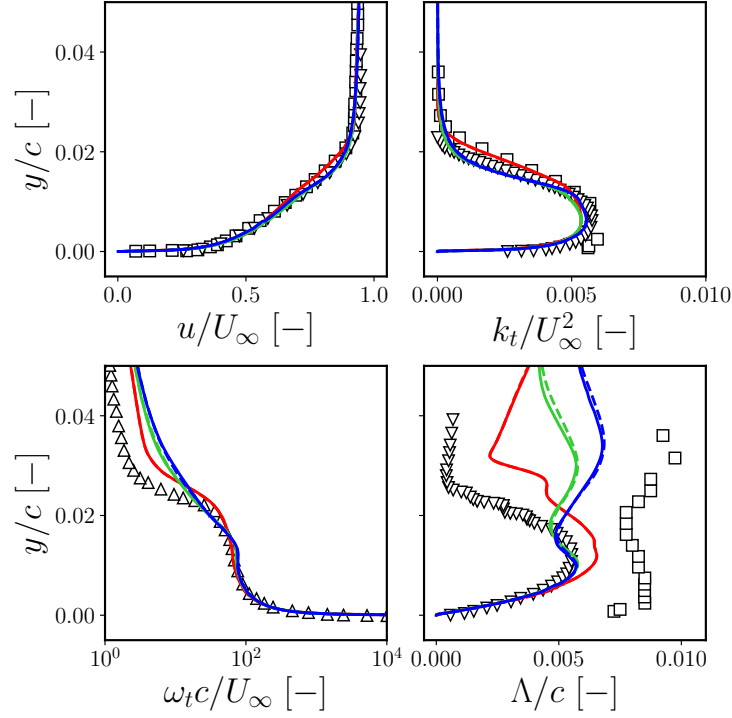


Figure 8.47: Vertical profiles of nondimensional near wake flow parameters, which are longitudinal velocity, u/U_∞ (upper left), turbulent kinetic energy, k_t/U_∞^2 (upper right), specific dissipation, $\omega_t c/U_\infty$ (lower left), and turbulent length scale, Λ/c , at a position $x/c = 0.9962$ (lower right), from the leading edge of the NACA 0012 airfoil. ($\square$) denotes experimental data from IAG LWT [127], (∇) for RANS results [127], and ($\triangle$) RANS results [170]. (—) denotes the STAR-CCM+ results for the suction side of the airfoils for coarse mesh ($y^+ \approx 5$), (—) for the medium mesh ($y^+ \approx 0.9$), and (—) for fine mesh ($y^+ \approx 0.2$), respectively. (---), (---), and (---) refers to the STAR-CCM+ results for pressure side of the airfoil, corresponding to results from the coarse, medium, and fine mesh configurations, respectively.

Since NACA 0012 is a symmetric airfoil, vertical profiles on both sides of the airfoil show the same pattern. Both velocity and turbulence kinetic energy profiles agree quite well with the existing RANS data and the experimental results, regardless of the mesh density being tested. For vertical profiles of specific dissipation and turbulent length scale, all the results from different mesh configurations compare fairly well with the available RANS data within the boundary layer, except for the results from the coarse mesh case, as it shows an overestimation around $y/c = 0.01$. The measured turbulent length scale profile shows a straight trend up to the boundary layer height, which was predicted by any of the RANS models. Different boundary layer parameters obtained at $x/c = 0.9962$, for

Table 8.10: Boundary layer (BL) parameters obtained at $x/c = 0.9962$ from three different mesh configurations for the NACA 0012 airfoil at 0° angle of attack.

Parameter	Symbol	Unit	Mesh density		
			Coarse	Medium	Fine
Edge velocity	U_e/U_∞	[—]	0.908	0.906	0.911
BL thickness	δ_b/c	[—]	0.023	0.023	0.026
BL displacement thickness	δ_d^*/c	[—]	0.006	0.006	0.006
BL momentum thickness	θ_m/c	[—]	0.004	0.003	0.003
Skin friction coefficient	C_f	[—]	0.0018	0.0018	0.0017
Wall-shear stress	$\tau_w/(\rho_\infty U_\infty^2)$	[—]	0.0007	0.0007	0.0007
Friction velocity	u_*/U_∞	[—]	0.027	0.027	0.027
Clauser parameter	β_c	[—]	6.472	5.866	6.121
Coles' wake parameter	Π	[—]	3.433	3.206	3.302

different mesh configurations, are presented in Table 8.10.

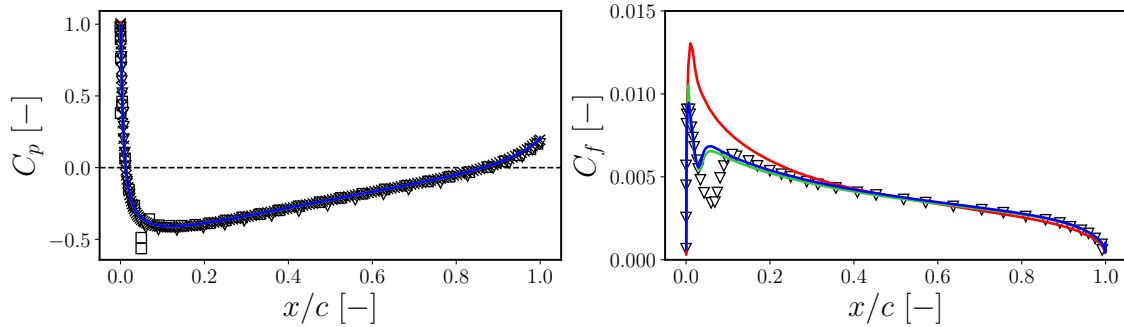


Figure 8.48: Pressure and skin friction coefficients (C_p and C_f) along the nondimensional chord of the NACA 0012 airfoil. ($\square$) denotes experimental data from IAG LWT [127], (∇) for RANS results [127], and ($\times$) XFOIL results [127]. (—) denotes the STAR-CCM+ results for the suction side of the airfoil for the coarse mesh ($y^+ \approx 5$), (—) for the medium mesh ($y^+ \approx 0.9$), and (—) for fine mesh ($y^+ \approx 0.2$), respectively. (---), (---) and (---) refers to the STAR-CCM+ results for the pressure side of the airfoil, corresponding to coarse, medium and fine mesh results, respectively.

Figure 8.48 presents the distributions of pressure and skin friction coefficients, C_p and C_f , respectively, along the chord of the NACA 0012 airfoil for different mesh configurations. The pressure coefficient distributions from the STAR-CCM+ model follow the experimental data and results from both XFOIL and RANS models found in the literature. The present RANS simulations consider fully turbulent flow conditions; therefore, no transition was observed at $x/c \simeq 0.065$, where tripping is applied to transition the boundary layer from laminar to turbulent in the experiments. On the other hand, the resolved C_f distribution for the coarse mesh configuration cannot capture the trend at the leading edge for $0 \leq x/c < 0.4$. This problem was not observed in C_p distribution because capturing C_f requires a much finer mesh and, therefore, a much smaller grid distance between the airfoil wall and the first grid point. This is why C_f results from medium and fine mesh configurations did not differ significantly. Neither the medium nor the fine mesh configuration can capture the reference C_f profile from DLR in the interval $0.025 < x/c < 0.15$.

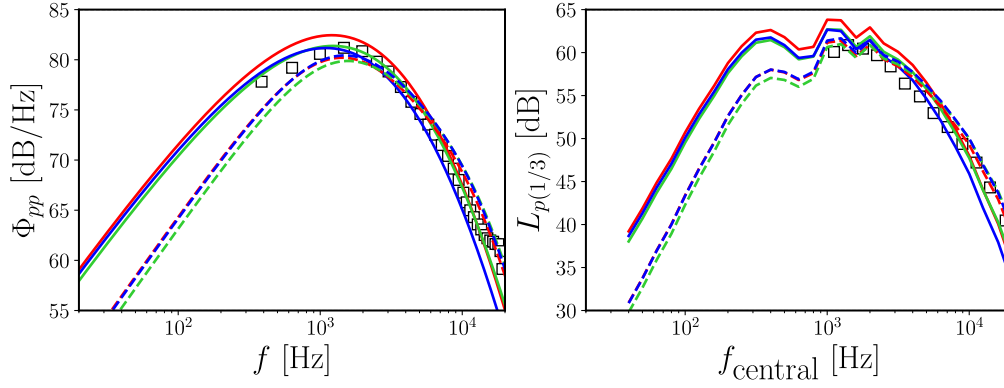


Figure 8.49: Wall-pressure spectra and sound pressure levels (SPL) in third-octave band predictions for the Lee (solid lines) and Kamruzzaman (dashed lines) models at $x/c = 0.99$ for the NACA 0012 airfoil. ($\square$) denotes experimental data from IAG LWT [127]. (—) denotes the results from the Lee+Amiet model for suction side of the airfoils for the coarse mesh ($y^+ \approx 5$), (—) for the medium mesh ($y^+ \approx 0.9$), and (—) for fine mesh ($y^+ \approx 0.2$), respectively. (---), (---) and (---) refers to the results from the Kamruzzaman+Amiet model for the suction side of the airfoil, corresponding to coarse, medium and fine mesh results, respectively. Note that the sound pressure levels given in the third-octave band include contributions from both sides of the airfoil.

Figure 8.49 displays results from different wall-pressure spectra (WPS or Φ_{pp}), obtained using the Lee and Kamruzzaman models, described in Section 4.2.4, and sound pressure levels in the third-octave band ($L_{p(1/3)}$) with respect to an observer located at $y/c = -2.5$. The wall-pressure spectra were obtained at $x/c = 0.99$, similar to those acquired in the experiments. It was seen that the best results were obtained using the medium mesh configuration in combination with Lee’s wall-pressure spectrum model. The results from the coarse mesh configuration overpredicted the experimental WPS around 1 kHz, although similar results were obtained at both low and high frequencies (up to ~ 15 kHz). Fine mesh results underestimated the experimental data of about 1 ± 0.5 dB for the frequency interval 1-10 kHz. The results from the medium mesh configuration agreed fairly well with the experimental data at all frequencies, up to 15 kHz. Kamruzzaman model underestimated the wall-pressure spectrum at low frequencies and overestimated it in the frequency interval $1 < f < 15$ kHz. For the predictions of $L_{p1/3}$, similar spectral distributions were observed as in the case of the wall-pressure spectrum, since Φ_{pp} is the main input of the Amiet’s trailing-edge noise model. In contrast to the accuracy observed in the determination of the wall pressure spectrum for frequencies $1 < f < 10$ kHz, results from the medium mesh configuration in combination with Lee’s WPS model overpredicted the SPL at 1 kHz. For frequencies above 10 kHz, the model results diverged from the experimental data. Overall, the best match was achieved when the medium mesh configuration was used with Lee’s WPS model. One should consider that employing a very fine mesh configuration does not always guarantee the most accurate results; thus, a mesh independence study is always necessary to determine the optimal set-up for trailing-edge noise modeling.

Effect of angle of attack on the aerodynamic properties and on the near wake flow of the isolated NACA 63(3)218 airfoil

The angle of attack, α , plays a crucial role in determining the aerodynamic properties of an airfoil, including the behavior of the boundary layer and its characteristics. In real atmospheric conditions, wind turbine blades experience atmospheric turbulent flow, which is one of the causes that make the angle of attack to constantly change.

In order to determine the dependence of the airfoil BL characteristics on the angle of attack, during the period of interest at the Høvsøre test site, the turbulent boundary layer of the NACA 63(3)218 airfoil has been modeled for angles of attack $\alpha = 6^\circ, 8^\circ, 10^\circ, 12^\circ, 14^\circ$, and 16° at a constant chord Reynolds number $Re_c = 3 \times 10^6$. This is a relevant analysis to determine the effective locations on both sides of the trailing edge of the airfoil in order to properly calculate the boundary layer parameters for noise modeling. At extremely high values of α , the boundary layer separates from the airfoil surface, resulting in unsteady and complex aerodynamic behavior, with appearance of vortex shed from the airfoil, as well as transient lift and drag forces [45]. Since the focus is given on the region subject to the adverse pressure gradient before the separation point on the suction side, boundary layer parameters have been extracted at different chord positions, from $x/c = 0.51$ to $x/c = 0.98$, depending on the location where the flow detaches from the surface. During the analyzed period of interest of the operating wind turbine, the resolved instantaneous angles of attack were always smaller than $\alpha = 16^\circ$.

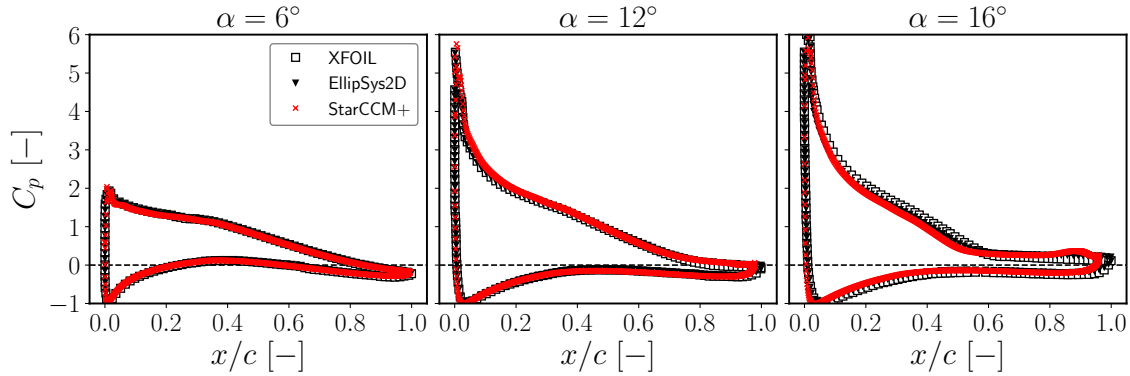


Figure 8.50: Representation of the pressure coefficient, C_p , along the normalized chord on the suction and pressure sides of the NACA 63(3)218 airfoil for $\alpha = 6^\circ, 12^\circ$, and 16° . The reference data from XFOIL and EllipSys2D have been adapted from Bertagnolio et al. [19].

Figure 8.50 displays the distribution of pressure coefficient along the nondimensional chord for $\alpha = 6^\circ, 12^\circ$, and 16° . For all the cases tested, the C_p profiles are in good agreement with the available RANS results and experimental data from the literature [19]. For $\alpha = 16^\circ$, the results from STAR-CCM+ are fairly lower in the interval $0.2 < x/c < 0.57$, with a slight overprediction for $0.8 < x/c < 0.91$. These differences may be due to the use of slightly different numerical set-ups.

The results from the present analysis and the data available in the literature show that

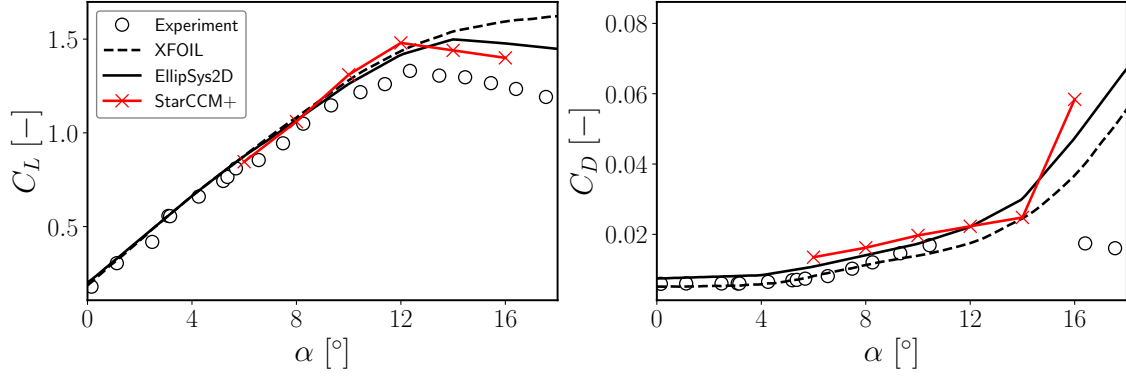


Figure 8.51: Variation of lift, C_L , and drag, C_D , coefficients with respect to the angle of attack, α , for the NACA 63(3)218 airfoil obtained for $Re_c = 3 \times 10^6$ and $M_\infty = 0.1731$. The reference data for experiments, XFOIL, and EllipSys2D, have been reproduced from Bertagnolio et al. [19].

this airfoil operates in conditions close to stall where the angle of attack is around $\alpha = 12^\circ$, what is observed in drop in lift estimated and measured for that angle of attack.

Figure 8.51 shows the change of lift, C_L , and drag, C_D , coefficients as a function of angle of attack for the NACA 63(3)218 airfoil. The results from the present analysis and the data available in the literature show that for the typical Re_c and M_∞ numbers analyzed, the angle of attack corresponding to maximum lift coefficient is around $\alpha = 12^\circ$. The C_L curve estimated from the present RANS simulations is consistent with results from XFOIL and EllipSys2D at all angles of attack; however, none of the numerical results match the experimental data for $\alpha \geq 10^\circ$. On the other hand, the C_D curves follow a similar pattern up to $\alpha = 14^\circ$, but significantly overestimate C_D at $\alpha = 14^\circ$ compared to the experimental data.

The vertical profiles given in Figure 8.52 on both sides of the NACA 63(3)218 airfoil show a different trend because of asymmetrical airfoil geometry and non-zero angle of attack. The nondimensional velocity profiles on the pressure side of the airfoil exhibit a steeper pattern than those on the suction side, resulting from higher observed turbulence levels in the latter. For $\alpha = 16^\circ$, a reverse flow ($\partial u / \partial y < 0$ at the wall) was observed due to flow separation near the trailing edge (not shown here). Because the boundary layer parameters were calculated at a location far from the trailing edge ($x/c = 0.51$) at $\alpha = 16^\circ$, the nondimensional velocity profile does not exhibit negative values at the wall. When separation occurred, the increase in TKE resulted in higher values of turbulent length scale for high values of angle of attack. For other conditions tested, all the boundary layer profiles extracted on the suction side increase gradually for α values greater than 10° . For the pressure side, the effect of α on the boundary layer profiles is more clear because the location at which the boundary layer parameters were calculated was kept constant; therefore, the flow became less turbulent when the angle of attack increased. The specific dissipation rate of turbulence kinetic energy on the pressure side reverts to its minimum value faster than on the suction side in all cases because the airflow on the pressure side

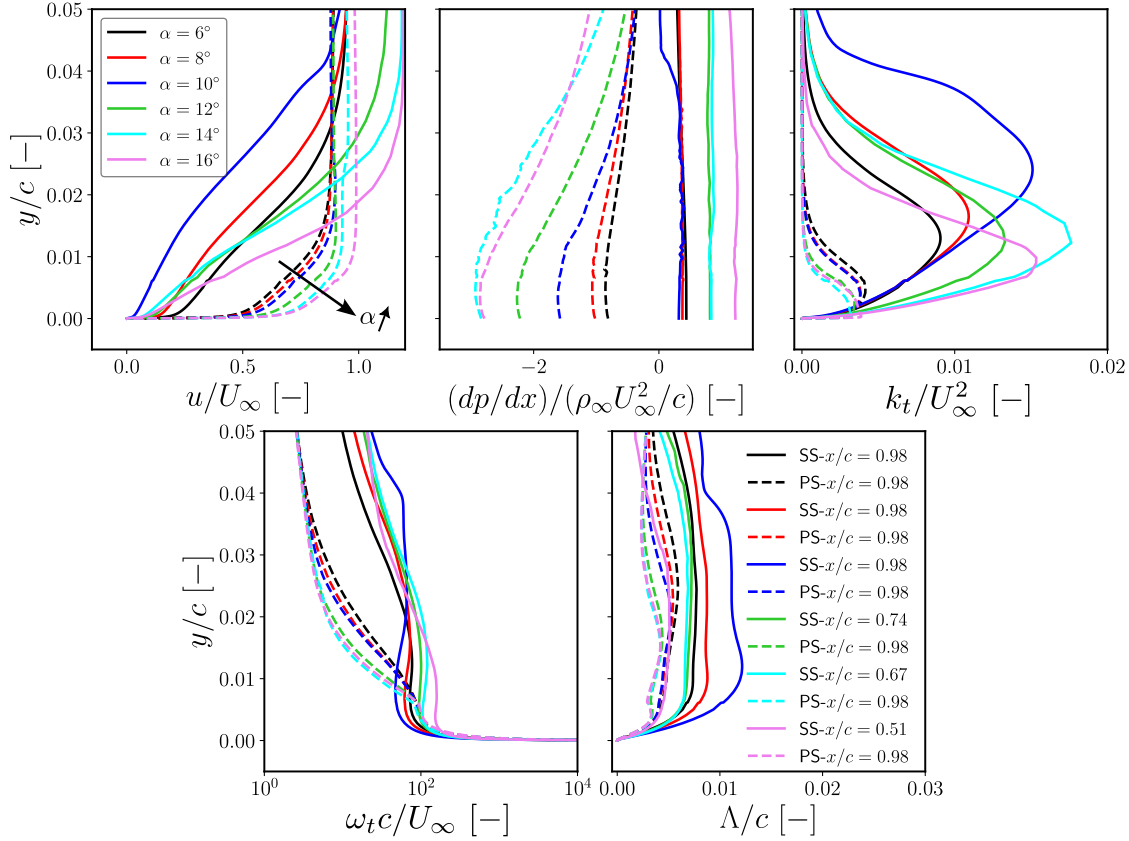


Figure 8.52: Nondimensional near wake flow parameters, which are longitudinal velocity, u/U_∞ (a), pressure gradient, $(dp/dx)/(\rho_\infty U_\infty^2/c)$ (b), turbulent kinetic energy, k_t/U_∞^2 (c), specific dissipation, $\omega_t c/U_\infty$ (d), and turbulent length scale, Λ/c (e), at different chord positions of the NACA 63(3)218 airfoil. Solid and dashed lines refer to the STAR-CCM+ results for the suction and pressure sides of the airfoil, corresponding to results from medium mesh configuration, respectively. The results correspond to the angle of attack values of $\alpha = 6^\circ, 8^\circ, 10^\circ, 12^\circ, 14^\circ$, and 16° represented by black, red, blue, green, cyan, and violet colors, respectively.

is less turbulent than on the suction side of the airfoil. Turbulent length scales at $\alpha = 10^\circ$ near the trailing edge are larger because of the formation of larger vortical structures passing over the trailing edge on the suction side.

The boundary layer parameters obtained for different angle of attack values from 2D RANS simulations are tabulated in Table 8.11. At all angles of attack, the Clauser pressure gradient parameter, β_c , for the pressure side is negative, indicating an FPG flow. Since the β_c values are smaller than -0.5 , Coles' wake parameter, Π , cannot be calculated on the pressure side as it has no real value. This also means that the wall-pressure spectrum cannot be determined from models using Π parameter as input, such as the Rozenberg, Lee, Catlet, and Hu & Herr models. β_c values are positive for the suction side, corresponding to a significant APG flow. This leads to clear differences in the observations of the respective contributions of the pressure side and suction side boundary layers to the wall-pressure and far-field noise spectra. The bias errors between the boundary layer parameters estimated by the presents RANS simulations and XFOIL are presented in Table 8.12. The trip

Table 8.11: Boundary layer (BL) parameters obtained for different values of angle of attack and chord positions on both sides of the NACA 63(3)218 airfoil.

Parameter	Symbol	Unit	Suction side, SS					
			$\alpha = 6^\circ$	$\alpha = 8^\circ$	$\alpha = 10^\circ$	$\alpha = 12^\circ$	$\alpha = 14^\circ$	$\alpha = 16^\circ$
			$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.74$	$x/c = 0.67$	$x/c = 0.51$
Edge velocity	U_e/U_∞	[—]	0.916	0.928	0.964	1.121	1.133	1.202
BL thickness	δ_b/c	[—]	0.038	0.045	0.075	0.042	0.030	0.035
BL displacement thickness	δ_d^*/c	[—]	0.012	0.016	0.026	0.016	0.016	0.012
BL momentum thickness	θ_m/c	[—]	0.006	0.007	0.009	0.007	0.005	0.005
Skin friction coefficient	C_f	[—]	0.0006	0.0003	0.00005	0.0002	0.0002	0.0002
Wall-shear stress	$\tau_w/(\rho_\infty U_\infty^2)$	[—]	0.0003	0.0001	0.00004	0.0001	0.0001	0.0002
Friction velocity	u_*/U_∞	[—]	0.016	0.012	0.006	0.012	0.010	0.012
Clauser parameter	β_c	[—]	9.932	17.758	73.113	38.681	42.315	40.992
Coles' wake parameter	Π	[—]	4.644	7.066	20.105	12.529	13.390	13.079
Parameter	Symbol	Unit	Pressure side, PS					
			$\alpha = 6^\circ$	$\alpha = 8^\circ$	$\alpha = 10^\circ$	$\alpha = 12^\circ$	$\alpha = 14^\circ$	$\alpha = 16^\circ$
			$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$
Edge velocity	U_e/U_∞	[—]	0.866	0.869	0.738	0.905	1.004	0.990
BL thickness	δ_b/c	[—]	0.019	0.017	0.013	0.012	0.076	0.010
BL displacement thickness	δ_d^*/c	[—]	0.003	0.003	0.002	0.002	0.005	0.0022
BL momentum thickness	θ_m/c	[—]	0.002	0.002	0.002	0.001	0.004	0.001
Skin friction coefficient	C_f	[—]	0.0026	0.0029	0.0031	0.0034	0.0035	0.0037
Wall-shear stress	$\tau_w/(\rho_\infty U_\infty^2)$	[—]	0.0096	0.0011	0.0011	0.0014	0.0017	0.0018
Friction velocity	u_*/U_∞	[—]	0.031	0.032	0.034	0.037	0.042	0.042
Clauser parameter	β_c	[—]	−1.962	−1.986	−2.257	−2.161	−6.209	−1.936
Coles' wake parameter	Π	[—]	—	—	—	—	—	—

option in XFOIL was not used.

The color maps of nondimensional longitudinal velocity, u/U_∞ , for various values of α at a constant chord Reynolds number of $Re_c = 3 \times 10^6$, are given in Figure 8.53. The color maps show no flow separation below $\alpha \leq 10^\circ$, and the boundary layer at the trailing edge was fully turbulent. At $\alpha = 10^\circ$, the flow was in transition from attached flow to separation. Above this value, the airflow began to detach from the suction side of the airfoil where the flow was subjected to higher curvature and higher adverse pressure gradient.

Table 8.12: Bias errors, $\mathbb{E}_{\text{bias}}$, of some boundary layer (BL) parameters obtained for different values of angle of attack and chord positions on both sides of the NACA 63(3)218 airfoil. The tabulated data presented herein correspond to bias errors between STAR-CCM+ and XFOIL.

Nondimensional parameter	Symbol	Unit	Suction side, SS					
			$\alpha = 6^\circ$	$\alpha = 8^\circ$	$\alpha = 10^\circ$	$\alpha = 12^\circ$	$\alpha = 14^\circ$	$\alpha = 16^\circ$
			$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.74$	$x/c = 0.67$	$x/c = 0.51$
Edge velocity	$\mathbb{E}_{\text{bias}}^{U_e}$	[—]	0.02175	0.01691	0.02092	0.08119	0.05027	−0.01713
BL thickness	$\mathbb{E}_{\text{bias}}^{\delta_b}$	[—]	−0.00005	−0.00521	0.01667	0.00214	−0.00884	0.00978
BL displacement thickness	$\mathbb{E}_{\text{bias}}^{\delta_d^*}$	[—]	0.00139	−0.00187	−0.00256	0.00072	−0.00164	0.00543
BL momentum thickness	$\mathbb{E}_{\text{bias}}^{\theta_m}$	[—]	0.00036	−0.00047	0.00083	0.00063	−0.00033	0.00139
Nondimensional parameter	Symbol	Unit	Pressure side, PS					
			$\alpha = 6^\circ$	$\alpha = 8^\circ$	$\alpha = 10^\circ$	$\alpha = 12^\circ$	$\alpha = 14^\circ$	$\alpha = 16^\circ$
			$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$	$x/c = 0.98$
Edge velocity	$\mathbb{E}_{\text{bias}}^{U_e}$	[—]	0.01644	0.00397	−0.02395	−0.03662	0.03549	−0.00324
BL thickness	$\mathbb{E}_{\text{bias}}^{\delta_b}$	[—]	0.00823	0.00805	0.00569	0.00662	0.07419	0.00853
BL displacement thickness	$\mathbb{E}_{\text{bias}}^{\delta_d^*}$	[—]	0.00173	0.00163	0.00135	0.00117	0.00405	0.00123
BL momentum thickness	$\mathbb{E}_{\text{bias}}^{\theta_m}$	[—]	0.00112	0.00108	0.00091	0.00083	0.00353	0.00100

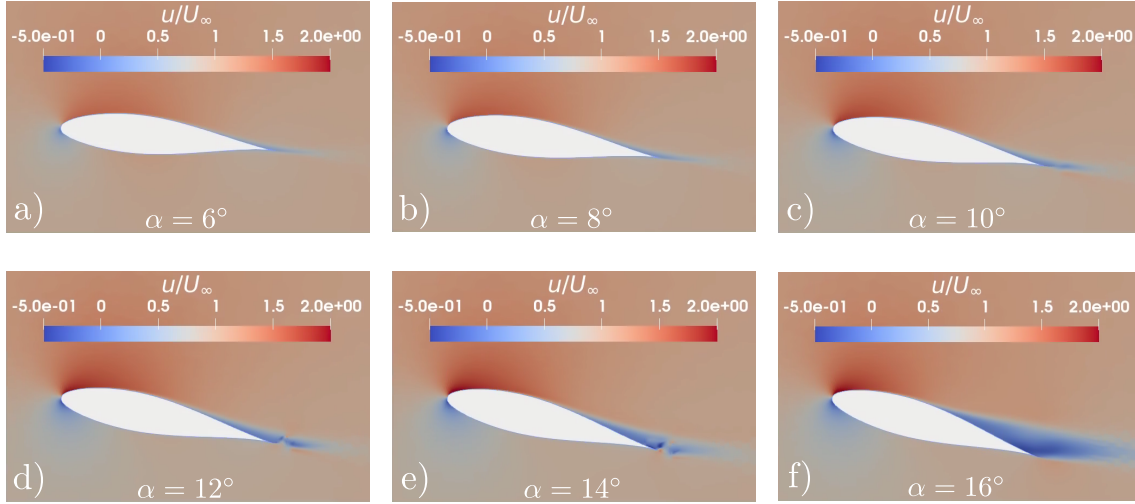


Figure 8.53: Color maps of normalized longitudinal velocity, u/U_∞ , for various angles of attack of the NACA 63(3)218 airfoil.

Figure 8.54 shows color maps of normalized turbulence kinetic energy, k_t/U_∞^2 . As explained earlier, large turbulent eddies, vortices and recirculation zones may form when the airflow separates from the airfoil surface at high angles of attack. Therefore, special care should be taken when choosing the appropriate location for calculating boundary layer parameters, especially when the flow detaches near the trailing edge. For instance, at $\alpha = 10^\circ$, a medium-sized turbulent eddy formed just after passing through the trailing edge (see Figure 8.54c), which could potentially affect the reliability of boundary layer parameters determined at $x/c = 0.99$, which is often used to characterize turbulent boundary layer and wall-pressure spectra. Therefore, these parameters were calculated at $x/c = 0.98$, slightly away from the tip of the trailing edge, for $\alpha \leq 10^\circ$ in order to avoid any flow disturbances that would have been caused by the formation of medium-sized turbulent eddies.

Effect of wall-pressure spectrum model estimates on isolated NACA 0012 and NACA 63(3)218 airfoil noise

The accuracy and reliability of the wall-pressure spectrum model estimation are important in estimating the trailing-edge noise of isolated airfoils. Since the selected wall-pressure model is one of the main inputs of Amiet's trailing-edge noise model, it can directly affect the accuracy of the predicted noise levels and frequency content. The magnitude of the boundary layer parameters calculated at the trailing edge of the airfoil determines the spectral content of the wall-pressure spectrum, and hence the spectral content of the trailing-edge noise. Therefore, these semi-empirical models must capture the correct frequency content to accurately predict the noise spectrum.

Figure 8.55 shows the estimates of different wall-pressure spectrum models in terms of wall-pressure and far-field noise spectra for the NACA 0012 and NACA 63(3)218 airfoils. $\alpha = 0^\circ$ and $\alpha = 6^\circ$ were chosen for NACA 0012 and NACA 63(3)218, respectively. The

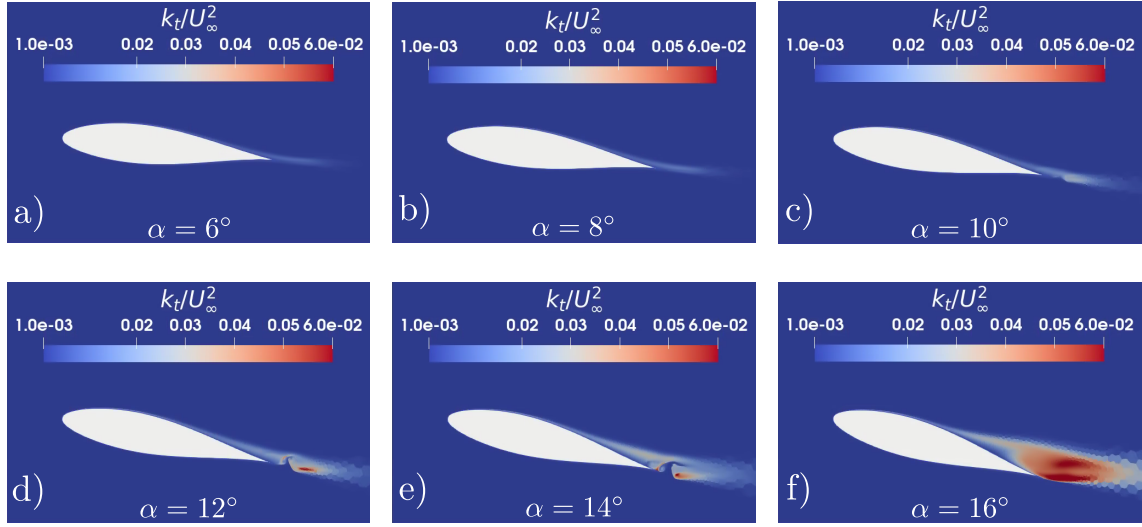


Figure 8.54: Color maps of normalized turbulence kinetic energy, k_t/U_∞^2 , for various angles of attack of the NACA 63(3)218 airfoil.

same flow and domain configurations, corresponding to the medium mesh configuration, given in Table 8.9 were used along with the Goody, Rozenberg, Kamruzzaman, Catlett, Hu & Herr, and Lee wall-pressure models. Even though it has been previously mentioned that only the Goody, Kamruzzaman, and Lee wall-pressure models are considered in this dissertation for in the determination of the full wind turbine noise, different wall-pressure models were also analyzed, in this preliminary phase, to determine the wall-pressure spectrum model that would give the best far-field noise estimates. In Figure 8.55a, the wall-pressure spectra calculated at $x/c = 0.99$ and the resultant far-field noise spectra are shown for the NACA 0012 airfoil. The best results were obtained by the Lee model for both spectra, with a very minor overestimation of about 1 dB in the 400-700 Hz frequency range. A reasonably well match was observed for frequencies $1 < f < 15$ kHz, yet the model underestimated the wall-pressure spectrum at very high frequencies. The Kamruzzaman model provided the second best-matching spectrum, with a slight underestimation of about 4-5 dB around 400 Hz. The model overestimates the wall-pressure spectrum at all frequencies between 3 kHz and 19 kHz. The other models could not capture the wall-pressure spectrum properly. Likewise, the Kamruzzaman and Lee models gave the most accurate results for the noise spectra, although their predictions were improvable. The maximum error of the Lee model, that is about 3 dB, was obtained for frequencies higher than 10 kHz, and the lowest error was obtained for frequencies of 1.5-2 kHz and 6-11 kHz. The results of the Lee and Rozenberg models overlapped because the Lee model, an extended version of the Rozenberg model, uses a methodology very similar to that used in the Rozenberg model. Note that, since the NACA 0012 is a symmetrical airfoil profile, the wall-pressure and noise spectra obtained on the suction and pressure sides are identical.

For the NACA 63(3)218 airfoil results, presented in Figure 8.55b, quite different spectra were obtained on both sides of the airfoil (due to asymmetric airfoil configuration). The present results from the Goody, Kamruzzaman, and Lee models were compared with

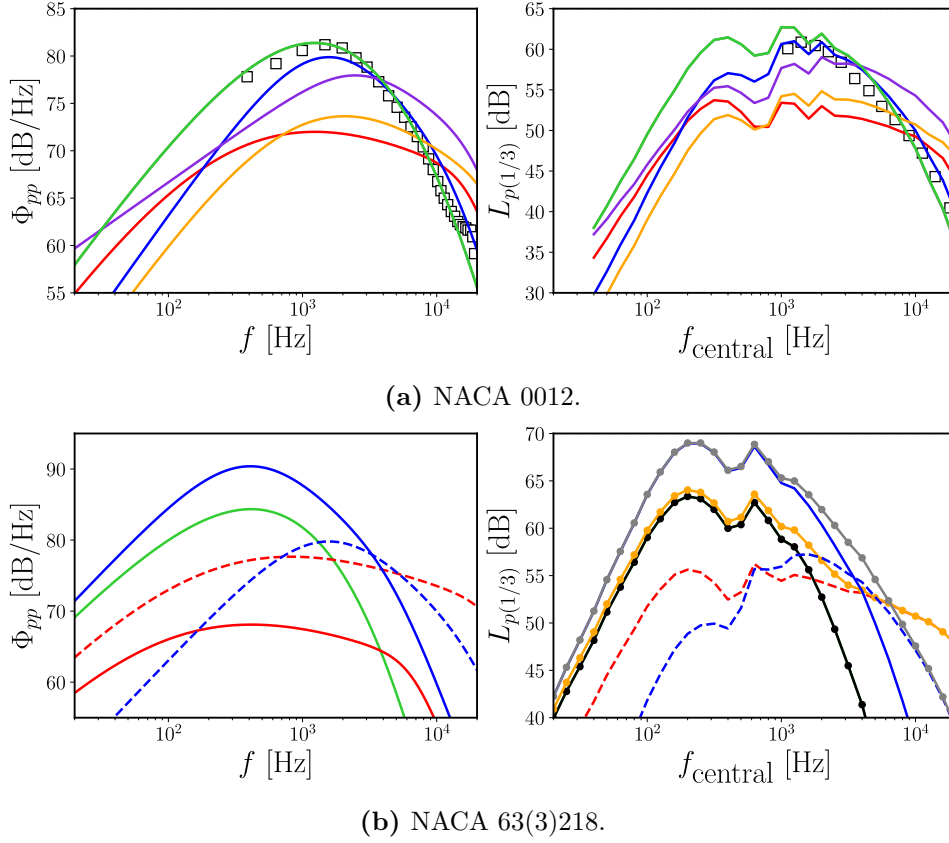


Figure 8.55: Wall-pressure spectra and sound pressure levels (SPL) in third-octave band predictions for different models at $x/c = 0.99$ for the NACA 0012 (a) and at $x/c = 0.98$ for the NACA 63(3)218 (b) airfoils. ($\square$) denotes experimental data from IAG LWT [127]. (—) denotes the contribution of the suction side of the airfoil, from the Goody+Amiet model, (—) from the Lee+Amiet model, (—) from the Rozenberg+Amiet model, (—) from Kamruzzaman+Amiet model, (—) from the Catlett+Amiet model, (—) from the Hu & Herr+Amiet model, respectively. (---), (---), (---), (---), (---), and (---) refer to the results from all models for the pressure side of the airfoil, respectively. Note that the sound pressure levels given in the third-octave band include the contributions from both sides of the airfoil for NACA0012. Only Lee and Kamruzzaman models are shown for NACA63(3)218 airfoil. (—) and (—) refers to the total SPL estimated by the Lee+Amiet and Kamruzzaman+Amiet models, respectively.

each other, as no experimental data were available for comparison. It is clear that the suction side of the airfoil contributes more to the spectrum at lower frequencies, whereas the pressure side often dominates the high-frequency trailing-edge noise. The Goody model shows significantly lower spectral content than the Lee and Kamruzzaman model predictions at all frequencies for the wall-pressure and noise spectra. The Lee model failed to predict the spectra on the pressure side, where FPG flow was observed, because the Lee model is mainly designed to account for APG flows [177]. For both spectra, the Kamruzzaman model gave the highest spectral content at all frequencies. The difference in total noise at 1 kHz predicted by the Lee and Kamruzzaman models is about 11 dB.

These findings reveal that the application of an APG model on the pressure side is questionable. For example, since the Lee model is designed to account for the effect of APG

flows, meaning it can work best on the suction side, it is recommended to combine it with a suitable wall-pressure model that takes into account FPG flow effects on the pressure side [170, 340]. Therefore, the Lee and Kamruzzaman models will be combined with the Goody model when modeling the trailing-edge noise emitted by the blades of the SWT-2.3-93 wind turbine at the Høvsøre test site.

Noise prediction of the real-scale SWT-2.3-93 wind turbine operating under unstable ABL conditions

The aim of this section is to incorporate the outcomes of the analyses performed in the previous sections into the noise analysis of the full-size SWT-2.3-93 wind turbine operating in realistic atmospheric flow conditions. Therefore, the methodology described in Sections 5.3.1 to 5.3.3 has been applied to the results from the WLGL model to generate the required inputs for the BATMAN code, the already described in-house code of the von Karman Institute for Fluid Dynamics (VKI) for noise modeling (see Section 5.3 for details).

Figure 8.56 shows the time series of the angle of attack, α , relative velocity, V_{rel} , and chord Reynolds number, Re_c , for the three blades of the generic SWT-2.3-93 wind turbine resolved by the WLGL model during the period of interest. A sudden drop in inflow wind velocity was observed around 15:57 (UTC) and no aerodynamic forces were calculated because the WLGL model predicted an extremely low inflow wind velocity. The modeled wind turbine was shut down for about 3-4 s because the inflow wind speed, determined at one rotor diameter upstream, was lower than the cut-in wind speed of the wind turbine. Apart from that, the angles of attack varied between 2° and 15° , whereas the values of relative velocity and chord Reynolds numbers did not change significantly at $r/R = 0.73$ and $r/R = 0.99$. Although the relative velocity values were higher at the tip of the blade, the local chord Reynolds numbers were smaller at the tip due to the smaller chord length.

The relative frequency of the angle of attack and chord Reynolds number given in Figure 8.57 refers to the rate or percentage of time that the angle of attack or Reynolds number occurs at different intervals over 30-min simulation of the ABL flow at the Høvsøre test site. These angle of attack or Reynolds number ranges are often categorized into bins or intervals, and the relative frequency is calculated by dividing the number of model predictions within each bin by the total number of estimates. The α and Re_c values shown in Figure 8.57 have been categorized into 50 bins. It has been found that the angles of attack values vary between $11^\circ \leq \alpha \leq 13^\circ$, with a probability of 5-10%. The angles of attack smaller than 11° cover $\sim 20\%$ of the total number of α estimates, whereas the angles of attack greater than 13° cover $\sim 9.2\%$ of the total number of estimates. For Re_c estimates, a quasi-uniform distribution was observed for the Re_c values falling into $3 \times 10^6 < \text{Re}_c < 6.5 \times 10^6$.

Based on the outcomes of the analysis on mesh sensitivity and appropriate probe locations to determine boundary layer parameters, the medium mesh configuration for the NACA

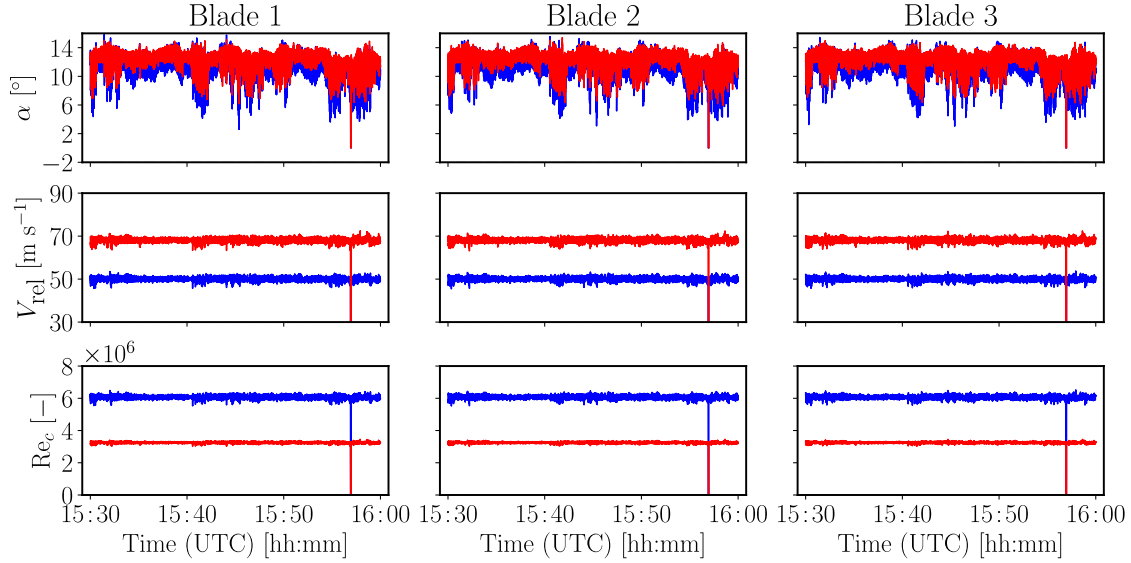


Figure 8.56: Time series of angle of attack, α , relative velocity, V_{rel} , and chord Reynolds number, Re_c , of the generic SWT-2.3-93 wind turbine represented by the WLGL model. (—) and (—) indicate the WLGL model estimations at $r/R = 0.73$ and $r/R = 0.99$ along the blades, respectively.

63(3)218 airfoil has been chosen to analyze all possible instantaneous angles of attack and Reynolds numbers recorded by the WLGL model during the period interest. In order to determine the minimum and maximum values of α and Re_c estimated by the WLGL model, α values were plotted as a function of Re_c for 12 segments along the outboard of the blade (i.e., $0.70 < r/R < 1.0$), as illustrated in Figure 8.58. Then, a Cartesian map was fitted to determine the values of α and Re_c , as well as the number of RANS simulations required to calculate the required boundary layer parameters. As simulating the entire time series of aerodynamic wind turbine data estimated by the WLGL model is impossible, this methodology becomes critical in reducing the total number of RANS simulations required for predefined angles of attack and corresponding Reynolds numbers. The boundary layer parameters corresponding to the selected values of α and Re_c were then

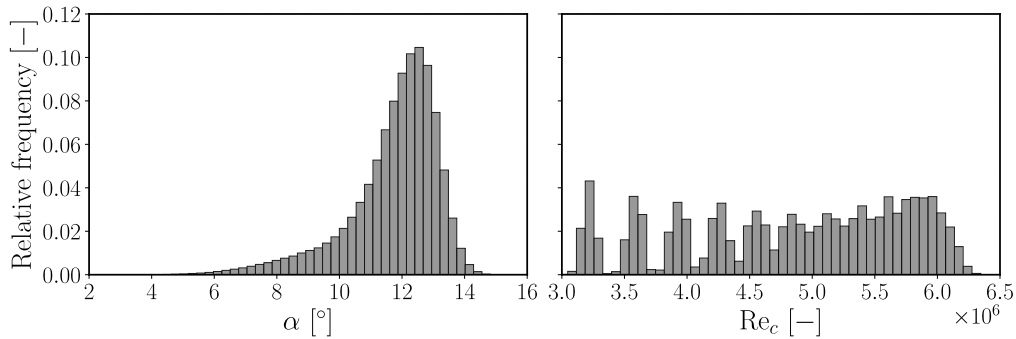


Figure 8.57: Relative frequency histogram for angle of attack, α (left), and chord Reynolds number of $\text{Re}_c = 12930228$ (right) (consisting of 30-min time series for 12 blade segments and 3 blades) data points estimated by the WLGL model during 30-min simulation for the period of interest. Both data have been grouped into 50 bins.

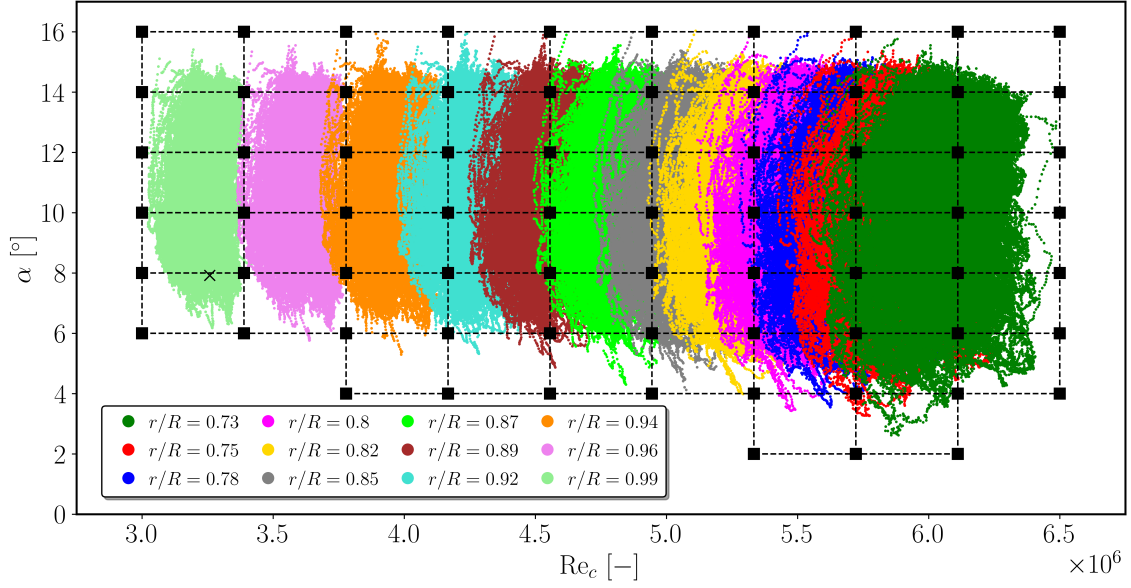


Figure 8.58: Illustration of instantaneous α values as a function of Re_c , estimated by the WLGL model for all blades and twelve segments that are uniformly distributed along the outboard of the blade. The data were recorded every 0.005 s during 30-min simulation. (■) symbols at the corners of each bounding box denote the Re_c and α inputs to be used in RANS computations. (×) indicates the location of arbitrarily selected values of the Reynolds number and the angle of attack for which the error analysis given in Table 8.13 was performed.

Table 8.13: Relative errors, E_{rel} , of some boundary layer (BL) parameters obtained on both sides of the NACA 63(3)218 airfoil. The tabulated data presented herein correspond to relative errors between the interpolated RANS data and an individual RANS simulation, with respect to the following input parameters: $\alpha = 7.92^\circ$, $Re_c \simeq 3258381$, $U_\infty \simeq 68.25 \text{ m s}^{-1}$, $c \simeq 0.6889 \text{ m}$ and $\rho_\infty = 1.226 \text{ kg m}^{-3}$.

Nondimensional parameter	Symbol	Unit	Suction side	Pressure side
Edge (external) velocity	$E_{rel}^{U_e}$	[%]	0.10145	0.02490
BL thickness	$E_{rel}^{\delta_b}$	[%]	1.63608	8.10939
BL displacement thickness	$E_{rel}^{\delta_d^*}$	[%]	0.19504	0.07957
BL momentum thickness	$E_{rel}^{\theta_m}$	[%]	0.75490	0.00429
Skin friction coefficient	$E_{rel}^{C_f}$	[%]	1.38587	0.07257
Wall-shear stress	$E_{rel}^{\tau_w}$	[%]	1.25647	0.02605
Friction velocity	$E_{rel}^{u_*}$	[%]	0.83095	0.00850
Clauser pressure-gradient parameter	$E_{rel}^{\beta_c}$	[%]	0.20091	0.22576
Coles' wake parameter	E_{rel}^{Π}	[%]	0.06450	—
Pressure-gradient	$E_{rel}^{dp/dx}$	[%]	1.44907	0.37967

interpolated by using the bilinear interpolation technique. The boundary layer parameters calculated based on the Cartesian map illustrated in Figure 8.58 are meticulously tabulated in Table A.1. The reader is referred to Section 5.3.2 for details of the methodology being applied herein.

Table 8.13 presents the relative errors between the interpolated RANS data and an individual RANS simulation, with respect to following input parameters: $\alpha = 7.92^\circ$, $Re_c \simeq 3258381$, $U_\infty \simeq 68.25 \text{ m s}^{-1}$, $c \simeq 0.6889 \text{ m}$ and $\rho_\infty = 1.226 \text{ kg m}^{-3}$. Note that these RANS simulations were performed using nondimensional inputs. It has been found that the relative errors between the interpolated BL data and the BL data calculated directly from the RANS simulations are pretty minor, except for the dimensionless BL thickness, δ_b/c , calculated on the pressure side. Since the interpolated and simulated non-dimensional BL thickness values, that are $(\delta_b/c)_{int} = 0.02776$ and $(\delta_b/c)_{sim} = 0.02568$, are very close to each other, the difference between these parameters is negligible. The subscript “*int*” and “*sim*” correspond to the interpolated and directly simulated BL parameters, respectively.

Figure 8.59 shows the variation of normalized edge (external) velocity, U_e/U_∞ , wall-shear stress, $\tau_w/(\rho_\infty U_\infty^2)$, boundary layer thickness, δ_b/c , and boundary layer displacement thickness, δ_d^*/c , from the RANS simulations of the NACA63(3)218 airfoil for different values of the angle of attack and Reynolds number. Note, data shown in Figures 8.59a to 8.59d were obtained on the suction side of the airfoil. The magnitude of the edge velocity increases when $\alpha > 10^\circ$. Since U_e is calculated using Equation (5.131), the increase in vorticity magnitude along the normal direction to the wall causes the edge velocities to be higher than unity. Smaller values of wall-shear stress for $\alpha \geq 10^\circ$ mean that the flow is weakly attached to the surface of the airfoil at that particular location on the suction side, and separation may occur if the airflow is disturbed or flow conditions change. The magnitude of the boundary layer thickness and boundary layer displacement thickness becomes larger for smaller Reynolds numbers and larger values of the angle of attack up to $\alpha = 10^\circ$. Beyond this value, the boundary layer parameters calculated on the suction side are extracted at different probe locations; thereby, a general conclusion cannot be drawn. The probe locations for $\alpha > 10^\circ$ were selected based on two criteria: $\beta_c < 50$ and $\tau_w/(\rho_\infty U_\infty^2) \geq 10^{-4}$. Both criteria ensure that the flow is still attached to the surface. Moreover, since β_c is a function of τ_w , when $\tau_w/(\rho_\infty U_\infty^2)$ becomes less than $\sim 5 \times 10^{-5}$ (i.e., strong APG flow), some wall-pressure spectrum models, like the Lee model, cannot be used anymore as it is validated for $\beta_c < 50$ [179].

Finally, Amiet’s semi-analytical model for trailing-edge noise described in Section 4.2.3 was applied to the full-size SWT-2.3-93 wind turbine. The wind turbine noise computation is based on a strip theory in which the blade is divided into smaller sections to account for the variation of wind flow conditions along the blade. Classical strip theory does not account for flow variation in the rotor plane, potentially leading to more significant deviations from measured noise levels when modeling noise emitted by wind turbines under highly unstable ABL conditions. The proposed approach overcomes this issue because it uses unsteady and non-uniform distributions of α and V_{rel} , saved at every $\Delta t = 0.005 \text{ s}$ during the period of interest. This means that different wall-pressure and noise spectra are calculated for different azimuth and radial positions along the blades. The radiated sound obtained for each azimuthal position is then integrated over the entire rotor, taking

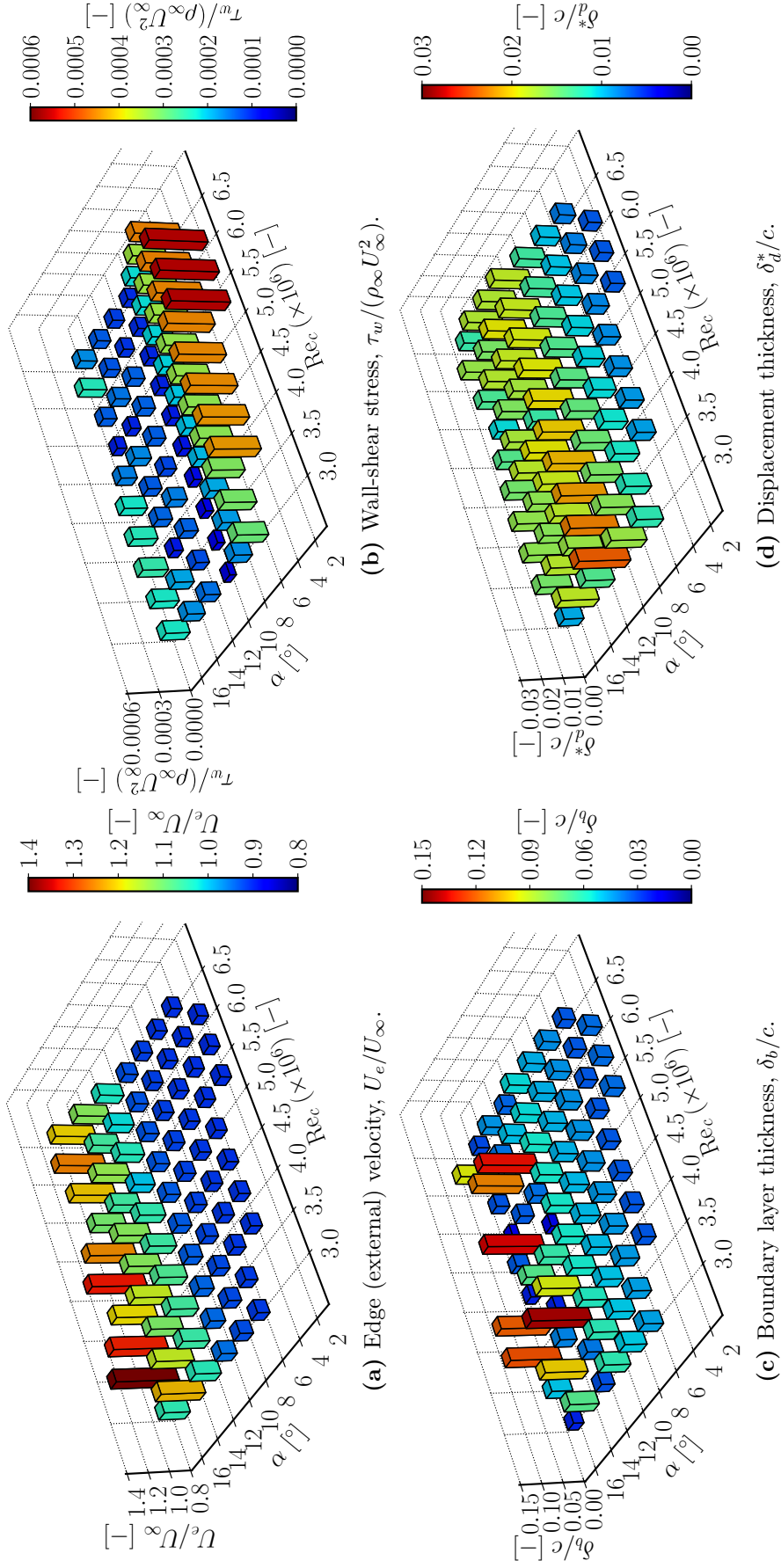


Figure 8.59: Representation of normalized edge (external) velocity, U_e/U_∞ (a), wall-shear stress, $\tau_w/(\rho_\infty U_\infty^2)$ (b), boundary layer thickness, δ_b/c (c) and boundary layer displacement thickness, δ_d^*/c (d) from the RANS simulations of the NACA63(3)218 airfoil. Data shown here were obtained on the suction side of the airfoil.

into account the Doppler effect, using Equation (4.48). The total trailing-edge noise level of the wind turbine is then found by summing over all strips.

Figure 8.60 shows the variations of mean and instantaneous values of α and V_{rel} in the rotor plane for the period of interest. The distribution of mean values of α shows that the change in α in the radial direction is about 1° for 30-min simulation, with minimum and maximum values of $\alpha_{min} \simeq 10.99^\circ$ and $\alpha_{max} \simeq 12.43^\circ$. Vertical wind shear is the dominant factor for the angle of attack variation causing the most drastic change at 15:34 (UTC) and 15:57 (UTC), whereas no significant change in local angle of attack in the rotor plane was observed at 15:45 (UTC). The instantaneous values of minimum and maximum angles of attack, i.e., $\alpha_{min} = 8.09^\circ$ and $\alpha_{max} = 13.01^\circ$, recorded at different azimuthal positions on 15:34 (UTC), demonstrate the necessity of such a dynamic approach in more accurate modeling of the wind turbine.

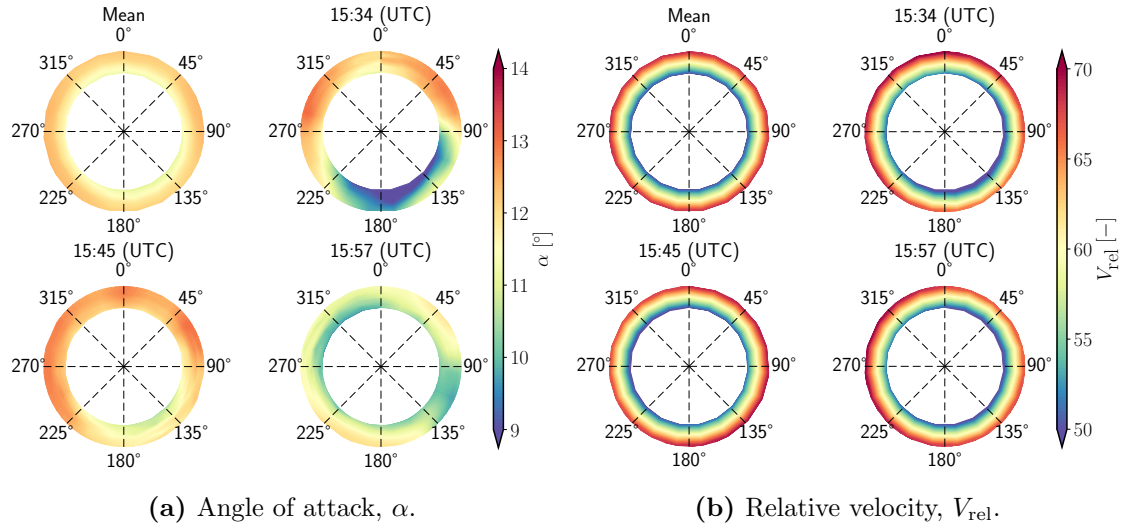


Figure 8.60: Variation of the angle of attack, α , (a) and relative velocity, V_{rel} , (b) in both azimuthal and radial directions in the rotor plane. The distributions of mean values are shown on the top left of each figure, whereas distributions of instantaneous values of α and V_{rel} are shown on the top right for 15:34 (UTC), on the bottom left for 15:45 (UTC) and on the bottom right for 15:57 (UTC), respectively. This represents an upwind configuration, with the wind turbine rotating in the clockwise direction.

Using the time-averaged angle of attack and relative velocity seen by the blades may result in more significant errors in the predicted noise levels, especially at low frequencies. As the airfoil angle increases, the low-frequency contributions from the suction side increase due to the thicker boundary layer and larger turbulent scales. On the other hand, high-frequency contributions from the pressure side also increase due to the thinner boundary layer and smaller turbulent scales [136]. However, the noise level variation in the high-frequency range is not very significant [51]. For the relative velocity distribution, the variation in the azimuthal direction was smaller than the change in the azimuthal distribution of the angle of attack for the analyzed periods. A more uniform radial distribution in relative velocity was observed, as V_{rel} increases significantly with increasing radial distance along the blade.

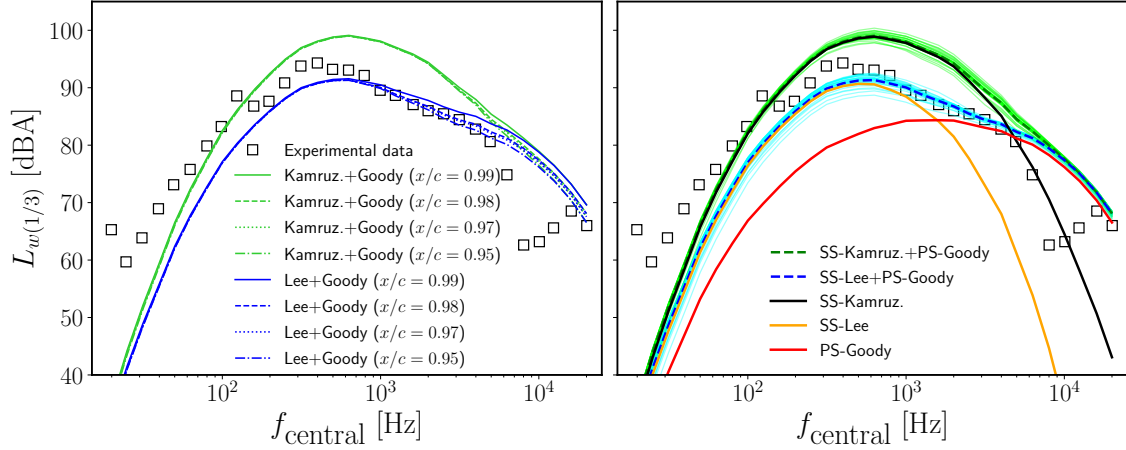


Figure 8.61: Comparison of the mean third-octave sound power level spectra ($L_{w(1/3)}$) obtained from the Kamruzzaman+Goody and Lee+Goody models at various chord locations on the suction side (left) and instantaneous $L_{w(1/3)}$ spectra obtained from the Kamruzzaman+Goody and Lee+Goody models on both sides at $x/c = 0.98$ (right). The instantaneous spectra represented by (—) and (—) were calculated from 1-min data during 30-min simulation. (---) and (-.-) indicate the mean spectra averaged over 30 instantaneous spectra from the Kamruzzaman+Goody and Lee+Goody models, respectively. The radiated power from the suction and pressure sides are indicated by (—), (—), and (—) for the Kamruzzaman, Lee, and Goody models, respectively.

Figure 8.61 shows the sensitivity of the predicted third-octave sound power level (SWL or L_w) spectra on the determination of probe locations on the suction side of the airfoil. The Kamruzzaman and Lee models were combined with the Goody model to account for APG and FPG flow effects on the suction and pressure sides of the airfoil, respectively. Since no general rule exists in the literature on where boundary layer parameters should be calculated on the trailing edge of the airfoil, four different probe positions, ranging between $x/c = 0.95$ and $x/c = 0.99$, were chosen for $\alpha \leq 10^\circ$ (regardless of different Reynolds number estimates). The aim was to investigate probe locations on either side of the airfoil for attached flow conditions. For angles of attack greater than 10° , the airflow passing through the trailing edge of the airfoil was transitioning from attached flow to separation; thus, the probe locations for high angles of attack were determined on the basis of the onset of separation. The mean SWL spectra from the Kamruzzaman+Goody model overestimated the measured spectrum for a large number of frequencies, ranging from 200 Hz to 4000 Hz, where the Lee+Goody model agreed quite well with the measured data for the same frequency range. The probe location on the suction side did not influence estimated spectra from both models, whereas both models overestimated the experimental data for frequencies greater than 4000 Hz when the probe location was shifted towards the trailing edge on the pressure side. This is because the magnitude of the edge velocity, U_e , and friction velocity, u_* , decreases; consequently, the time scale ratio of pressure, $R_T = (\delta_b/U_e)/(\nu/u_*^2)$, becomes larger and the spectral content of the wall-pressure spectrum shifts towards higher frequencies [112]. This shift towards higher frequencies causes a gradual increase in the wall pressure spectrum at higher frequencies. Therefore, $x/c = 0.98$ was chosen to calculate the boundary layer parameters from both models in this work. The

instantaneous spectra calculated from 1-min data over the period of interest indicate that a difference in estimated noise levels at different frequencies (e.g., $100 \leq f \leq 10000$ Hz) can vary up to ~ 2 dBA, independent of the wall-pressure models analyzed herein.

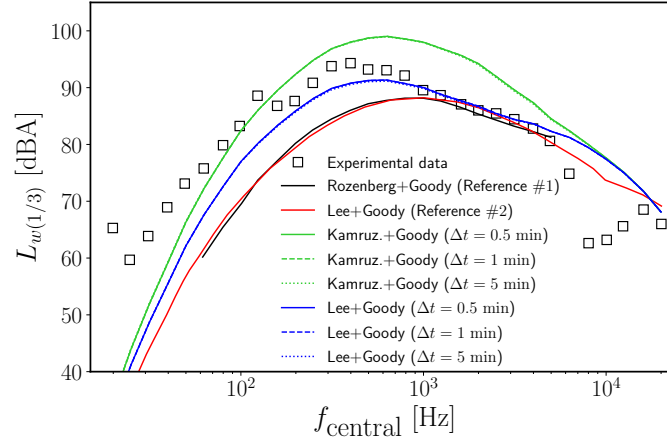


Figure 8.62: Sensitivity of the modeled third-octave sound power level results to data recorded at $\Delta t = 0.5$ -min, $\Delta t = 1$ -min, and $\Delta t = 5$ -min time intervals for the Kamruzzaman+Goody and Lee+Goody models. The experimental data has been reproduced from Leloudas [183], whereas Reference #1 and Reference #2 data have been reproduced from Tian [340] and Bériot et al. [17], respectively.

A sensitivity analysis of the modeled third-octave sound power level results from data grouped into $\Delta t = 0.5$ -min, $\Delta t = 1$ -min and $\Delta t = 5$ -min time intervals for the Kamruzzaman+Goody and Lee+Goody models is presented in Figure 8.62. The boundary layer parameters were calculated at $x/c = 0.98$ from the instantaneous angle of attack and relative velocity data stored into bins of $\Delta t = 0.5$ -min, $\Delta t = 1$ -min and $\Delta t = 5$ -min intervals during 30-min simulation in order to investigate the dependence of the noise spectra on the variation of the magnitude of boundary layer parameters. For smaller values of Δt , the variability in the angle of attack and relative velocity increases as more samples are taken into account in modeling the wall-pressure and noise spectra. Nonetheless, no significant difference in the spectra was observed when more samples were considered; thereby, data obtained at every $\Delta t = 1$ -min were used for further analysis. The results from Tian [340] (Reference #1) and Bériot et al. [17] (Reference #2) were obtained from the time-averaged hub height inflow velocity, $\bar{U}_{hub} = 8 \text{ m s}^{-1}$. Non-uniformity of the inflow on the WT rotor and other aerodynamic quantities, such as the angle of attack and relative velocity in the azimuthal direction were not taken into account by these models used in the reference papers. These reference data were based on strip theory applied to full blade span, with slightly different airfoil configurations along the blade. Tian and Cotté [341] assumed that the blade sections were NACA 63(3)415 airfoils, whereas Bériot et al. [17] used the same strategy for the airfoil distribution along the blade, as reported in Churchfield [54]. This may explain why similar results were obtained for both reference data, despite the different airfoil types and distributions used to model the SWT-2.3-93 wind turbine trailing-edge noise. The results from Bériot et al. [17] were obtained with a spanwise discretization of 11 strips along the blade and 5 azimuthal integration points in the rotor plane, whereas

12 strips in the last 30% of the blade with 20 azimuthal integration points were used in the present model. Good agreement is observed between the predicted and reference peak frequencies, and a fair estimation of the spectral shape confirms that the presented methodology for trailing-edge noise is adequate.

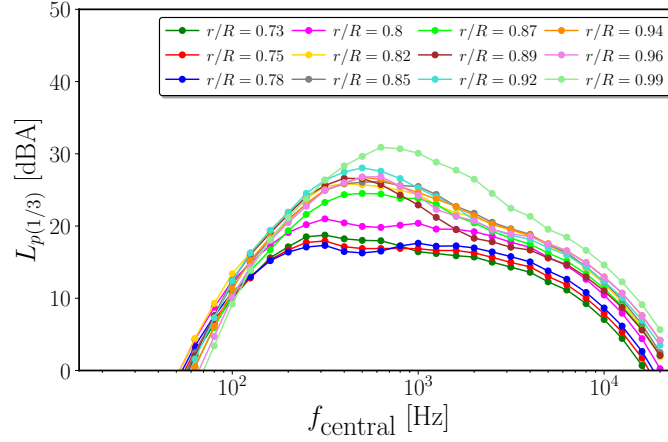


Figure 8.63: Variation of the third-octave sound pressure level spectra with A-weighting filter at different radial positions along the last 30% of the blade.

Figure 8.63 displays the variation of third-octave sound pressure level spectra with A-weighting filter along the last 30% of the blade. Because noise radiation from outboard blade sections, typically $r/R > 0.70$, is due to larger relative velocity and thicker boundary layer formed on the airfoil, the noise emitted from the blade tip dominates the SPL spectrum for frequencies $f \geq 630$ Hz. At low frequencies, the difference in noise levels in the range $0.73 \leq r/R \leq 0.99$ becomes smaller than those estimated at mid frequencies. As the airfoil approaches the tip, its chord length decreases, leading to a reduction in separation length and subsequently lowering the radiated noise levels caused by the formation of tip vortices [243].

Figure 8.64 shows the variation of the mean and instantaneous wall-pressure and third-octave SPL spectra in the rotor plane at different frequencies, ranging from $f \simeq 100$ Hz to $f \simeq 10000$ Hz. The wall-pressure and noise spectra are non-uniform in both azimuthal and radial directions. The source maps show the direction of the sound emitted from the wind turbine for an observer 100 m downwind. For the mean source maps, the source distribution was averaged over approximately 420 revolutions, corresponding to 30 minutes, while the instantaneous source maps were calculated at that particular time indicated in the figures. The source maps for the wall pressure spectra at three different frequencies show that although the relative velocity increases with increasing radial distance, the contribution from the tip of the blade is not always maximum. This is because the wall pressure spectrum is an indirect function of the chord Reynolds number and the chord Reynolds number does not always increase linearly along the blade due to the change in chord length (see Figure 8.56). For the wind turbine considered in this study, depending on the incoming wind speed, the maximum values of the wall-pressure spectra were obtained in the range $r/R = 0.80$ - 0.85 where the chord Reynolds number was maximum. At very high

frequencies, such as $f = 10$ kHz, the wall-pressure spectra were generally dominated by the tip of the blade. Lower levels of the wall-pressure spectra were observed between 270° and 0° , due to lower relative velocity seen by the blades. This strong asymmetrical source pattern that causes the swishing noise during the passage of the blades can be explained by trailing edge noise directivity and convective amplification. Similar results to those found in the literature were also obtained for noise source maps [244]. It can be seen that most of the noise was radiated from the outer part of the blades at all frequencies during the downward movement of the blades. However, the third-octave SPL spectra were not always dominated by the tip of the blade. The reason why the outboard of the blade contributes more to the noise spectra is that the aerodynamic noise scales with the fifth or sixth power of the wind speed [243].

Figure 8.65 shows the time signals of the A-weighted overall sound pressure level, OASPL, with respect to a receiver at 100 m downstream of the wind turbine. Since the reference noise data, obtained from the mean of 10 s average data of total noise, was digitized from the time series of the sound pressure level in the third-octave band reported in Leloudas [183], an uncertainty of ± 2 dBA was added to account for data digitization errors. The results from the Kamruzzaman+Goody model did not show variations in the predicted OASPL throughout the simulation, while small variations of about ~ 0.5 dBA were observed in the results of the Lee+Goody model at different chord locations on the suction side for $\alpha \leq 10^\circ$. The Lee+Goody model gave better results than the Kamruzzaman+Goody model, with a maximum error of about 6 dBA around 15:56-15:57 (UTC). It is relevant to remain that the modeled data corresponding to trailing-edge noise are compared with the total noise reported in the reference paper.

Figure 8.66 illustrates the sensitivity of the modeled third-octave OASPL results calculated from the data recorded at $\Delta t = 0.5$ -min, $\Delta t = 1$ -min, and $\Delta t = 5$ -min time intervals for the Kamruzzaman+Goody and Lee+Goody models. Contrary to what has been observed in Figure 8.62, an important difference was found in predicted OASPL levels. This indicates that the irregularity of wind flow can be better incorporated into the modeled noise levels if more samples are taken. However, direct comparison with reference data is neither straightforward nor accurate, as the estimated OASPL only considers trailing-edge noise. In contrast, the data reported in the reference paper includes the total noise emitted by the wind turbine, which considers all noise sources, such as trailing-edge noise, turbulent inflow noise, separation noise, trailing-edge bluntness noise, etc. It is important to note that the reference OASPL data was digitized from the SPL data reported in Leloudas [183]; thus, an uncertainty of ± 2 dB was added in order to account for data digitization errors.

Finally, the dependence of wind turbine noise on the incoming wind speed was investigated, and the corresponding measured data, a second-order polynomial fit through those measurement points, including a standard deviation with 95% confidence interval, as well as the Lee+Goody model estimates for the trailing-edge noise are shown in Figure 8.67. Calculations were performed for a range of wind speeds, and the overall sound power level

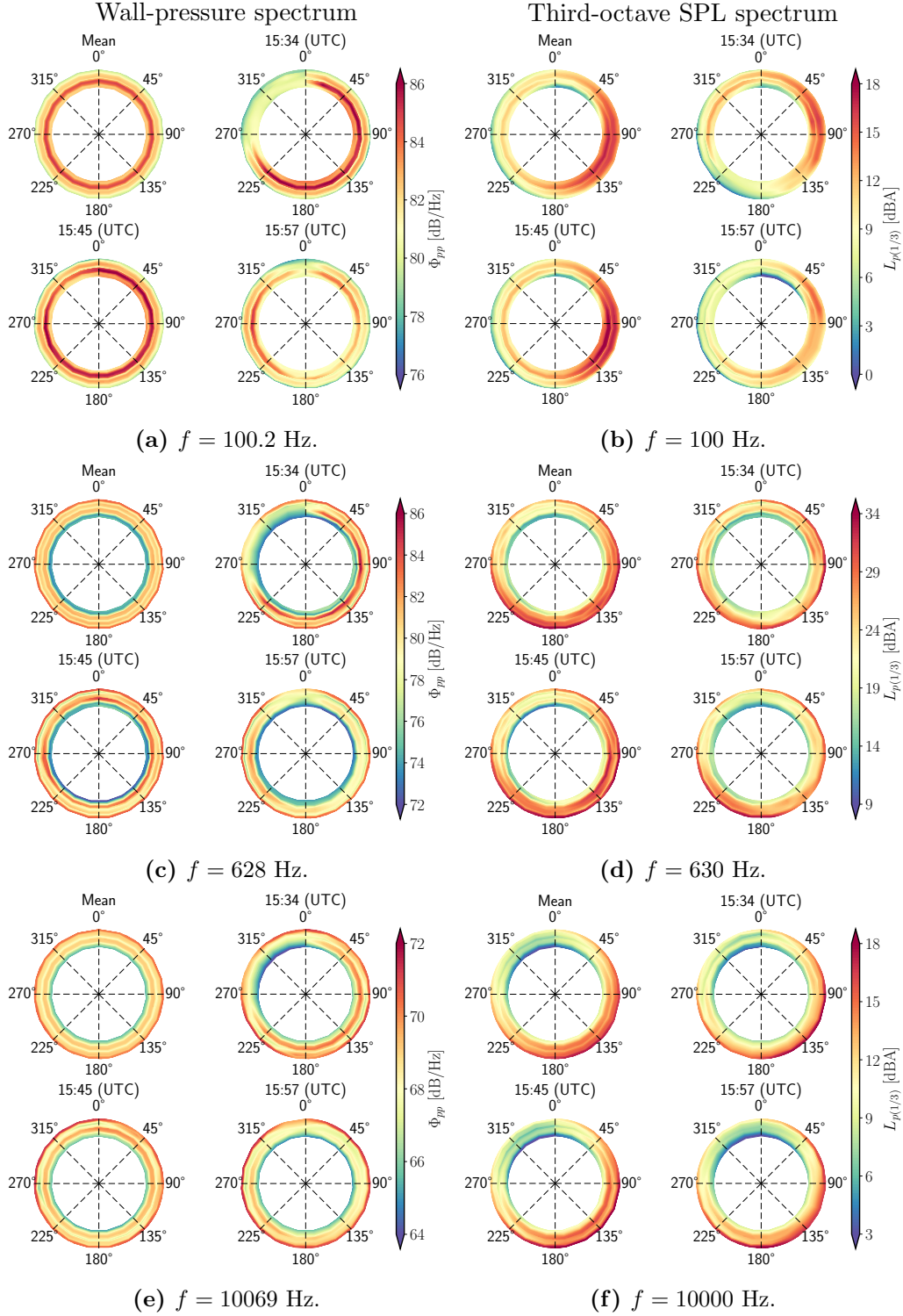


Figure 8.64: Variation of the wall-pressure spectra, Φ_{pp} , (a,c,e) and third-octave band spectra of sound pressure level, $L_{p(1/3)}$, (b,d,f) in the rotor plane for different frequencies. Note, the wall-pressure spectra are non-uniform in both azimuthal and radial directions, whereas the sound power level spectra are uniform in the azimuthal direction, but vary in the radial direction. The distributions of mean values are shown on the top left of each figure, whereas distributions of instantaneous values of Φ_{pp} and $L_{p(1/3)}$ are shown on the top right for 15:34 (UTC), on the bottom left for 15:45 (UTC) and on the bottom right for 15:57 (UTC), respectively. This represents an upwind configuration, with the wind turbine rotating in the clockwise direction.

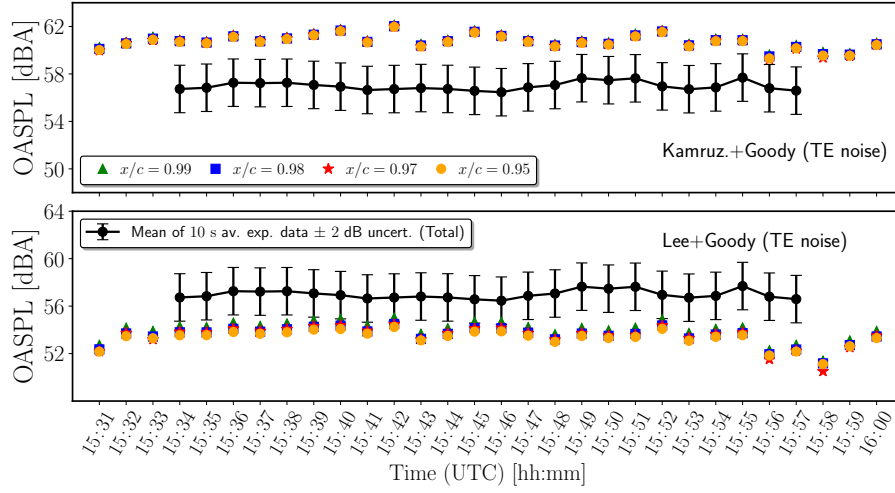


Figure 8.65: Comparison of the overall sound pressure level, OASPL, with A-weighting filter, obtained from the Kamruzzaman+Goody and Lee+Goody models at various chord locations on the suction side for $\alpha \leq 10^\circ$. Reference data from Leloudas [183] have been digitized from the time series of the A-weighted sound pressure level reported in the reference paper. An uncertainty of ± 2 dBA was added to take into account the data digitization errors.

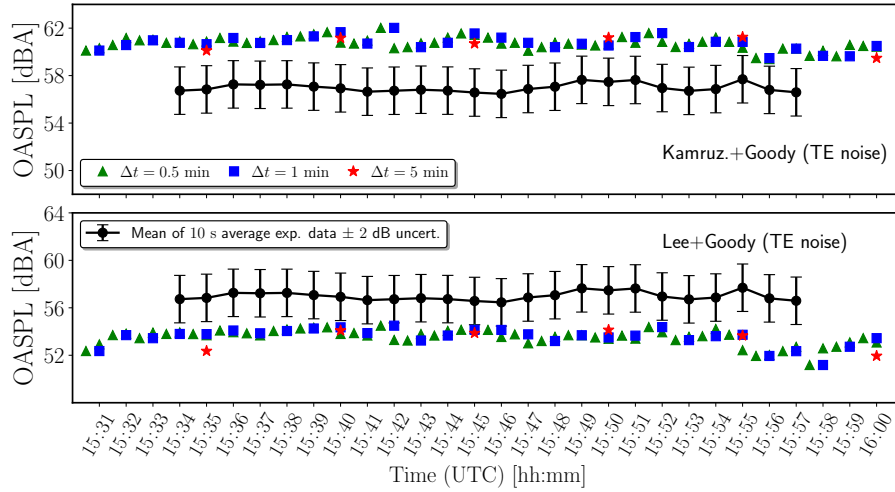


Figure 8.66: Sensitivity of the modeled overall sound pressure level, OASPL, with A-weighting filter to the OASPL results calculated from the data grouped into $\Delta t = 0.5$ -min, $\Delta t = 1$ -min, and $\Delta t = 5$ -min time intervals for the Kamruzzaman+Goody and Lee+Goody models. Reference data from Leloudas [183] have been digitized from the time series of the A-weighted sound pressure level reported in the reference paper. An uncertainty of ± 2 dBA was added to take into account the data digitization errors.

was determined by integrating the predicted rotor noise levels over all frequencies. It was observed that the modeled noise levels increase gradually with increasing wind speed, except for wind speeds in the range $6.4\text{--}7.6\text{ m s}^{-1}$ and captures the right trend, despite minor differences in estimated noise levels due to lack of contributions of other noise sources. The irregularity in the modeled noise levels was probably due to the larger angles of attack seen by the blades during a wind flow passage. Due to sudden changes in wind speed and wind direction, the wind turbine probably did not have enough time to yaw into the

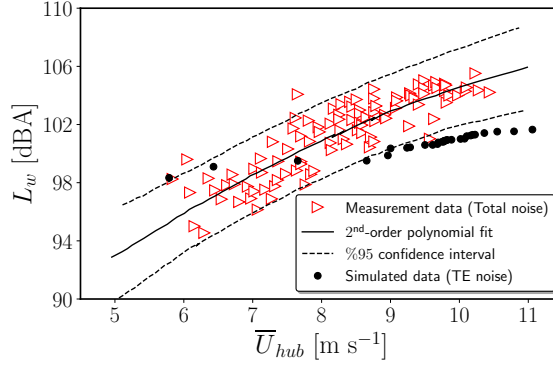


Figure 8.67: Comparison of estimated and measured sound power levels of the wind turbine with respect to inflow hub height wind speed. The sound power levels were calculated at 100 m downstream of the wind turbine. Note that noise data from the model includes only trailing-edge noise, whereas measured data corresponds to the total noise (adapted from Leloudas [183]).

correct position, which may have resulted in higher noise levels at lower wind speeds.

8.2.6 Conclusions

A comprehensive analysis has been carried out based on aerodynamic and aeroacoustic modeling of the full-size SWT-2.3-93 wind turbine installed at the Høvsøre test site in Denmark, including the determination of the ABL flow conditions at the site, wake modeling and performance assessment of the wind turbine, as well as noise modeling of the isolated NACA 0012 and NACA 63(3)218 airfoils, and near-field noise modeling of the real-scale 2.3MW wind turbine. First of all, a sensitivity analysis based on mesoscale ABL flow modeling was performed in order to determine the appropriate reanalysis dataset and PBL models, which have a significant effect on the accuracy of the model estimates of local weather conditions. After the best-practice case set-up was determined, a mesoscale-microscale coupled wind turbine simulation, the so-called WLGL model simulation, was performed to model the ABL flow-wind turbine interaction as well as to investigate the possible wake effects on the measurements taken at Høvsøre met mast, which is located a few rotor diameters downstream of the wind turbine. It was found that the mesoscale model is not able to predict local weather conditions at the met mast location, as it does not account for the wind turbine wake effects. However, when placing a wind turbine in mesoscale-microscale coupled WLGL simulations, it was observed that the wind turbine wake influenced the measured weather data at the met mast location since the met mast partially lay in the wake of the wind turbine during the measurement campaign held on 30/05/2006 between 15:34-15:57 (UTC). The WLGL model results for the wind speed profile were consistent with measurements at the mast position, particularly along the wind turbine rotor. Nonetheless, the vertical profile of the modeled wind direction underestimated the experimental data, possibly due to the incorrect selection of the control point location in the near wake, as the wind turbine wake highly influenced the predicted wind direction profile. No comparison for the wake velocity deficit profiles and the aerodynamic response of the wind turbine was made due to the lack of experimental data.

Next, a validation analysis based on 2D RANS modeling of the NACA 0012 airfoil was performed in order to determine the optimum model configurations and domain set-up for noise modeling of the NACA 63(3)218 airfoil to be incorporated in the trailing edge noise analysis emitted by the blades of a full-scale operational wind turbine. The NACA 0012 airfoil was chosen due to the availability of both aerodynamic and aeroacoustic data in the literature. The computational set-up, determined after performing a mesh sensitivity analysis on the basis of near wake flow, surface pressure spectra, and far-field noise, used for the NACA 0012 was employed in the 2D RANS modeling of the NACA 63(3)218 airfoil. Three different mesh configurations based on different values of y^+ , that are $y^+ = 5, 0.9$, and 0.2 , were tested along with the wall-pressure spectrum models of Goody, Rozenberg, Kamruzzaman, Catlett, Hu & Herr, and Lee. Quite satisfactory results were found for the mean profiles of velocity, turbulent kinetic energy, specific dissipation rate, and turbulent length scale when compared with the available RANS results and experimental data reported in the literature. The mesh sensitivity analysis suggested that using a mesh configuration with nondimensional wall distance of $y^+ = 0.9$ would be adequate for analysis of trailing-edge noise of the NACA 63(3)218 airfoil since no significant difference between the results from the fine and medium mesh configurations, corresponding to $y^+ = 0.2$ and $y^+ = 0.9$, respectively, was observed. After that, the effect of the angle of attack on the aerodynamic properties and near wake flow characteristics of the NACA 63(3)218 airfoil was analyzed in order to determine the optimum chord positions to calculate the boundary layer parameters to be used as input to the semi-analytical Amiet's model for trailing-edge noise. This analysis has shown that suction side boundary layer detaches for angles of attack larger than 12° , meaning that the turbulent boundary layer parameters cannot be calculated at the very tip of the trailing edge. Consequently, the chord locations of $x/c = 0.51, 0.67, 0.74$, and 0.98 were chosen to calculate boundary layer parameters, wall-pressure spectra, and far-field noise for the angles of attack varying between $6^\circ \leq \alpha \leq 16^\circ$ on the suction side. For the pressure side, it was set to $x/c = 0.98$ for all angles of attack. The present results of the distributions of pressure, lift, and drag coefficients of the airfoil agreed reasonably well with the available data. Wall-pressure and third-octave sound pressure level spectra obtained using combinations of the Goody, Kamruzzaman, and Lee models were plotted against each other for qualitative comparison.

Finally, near-field noise analysis of the 93 m rotor diameter 2.3 MW wind turbine was carried out in realistic atmospheric ABL flow conditions at the Høvsøre test site. An explicit coupling strategy, based on the results of the previous sensitivity analyses, between the WLGL model and BATMAN code was proposed to account for non-uniform turbulent ABL flow conditions observed during the measurement period. Results of the coupled WLGL-BATMAN model were compared to data from the literature. Two sensitivity analyses were conducted to investigate the dependence of the noise spectra on the suction-side probe location and the effective time interval required to incorporate the variation in ABL flow conditions modeled during the 30-min simulation. The latter is an important study to explore the influence of the local angle of attack and relative velocity unsteadiness and non-uniformity on predicted sound power levels. The smallest errors were found

when the third-octave noise power level spectra were calculated at $x/c = 0.98$ on the suction side for the angles of attack below $\alpha \leq 10^\circ$ (Lee+Goody model). The results from the Kamruzzaman+Goody model underestimated the noise spectra at all frequencies. Since the final form of the sound power level spectrum was obtained by averaging the instantaneous spectra calculated at every $\Delta t = 0.5\text{-min}$, $\Delta t = 1\text{-min}$, or $\Delta t = 5\text{-min}$, no significant difference was observed when the number of instantaneous spectra was increased (see noise source maps calculated in the rotor plane Figure 8.64 for details). The sound power level predictions with respect to an observer located at 100 m downstream of the wind turbine are in good agreement with measurements at high frequencies when the Lee+Goody model is used, with a significant underestimation at low frequencies, which is due to not taking into account the contribution of the turbulent inflow noise. Next, the contributions of different blade segments to the estimated sound power level spectrum were analyzed by plotting the spectra for 12 radial stations along the blade. At approximately 630 Hz, where the maximum noise levels were achieved, the tip of the blade, as well as the region in the interval $r/R = 0.80\text{-}0.85$, were found to contribute the most to the predicted noise levels, which is similar to that at around 10 kHz. On the other hand, at lower frequencies, the contribution from the blade tip became less and was dominated by the noise radiated from a region between $r/R = 0.82\text{-}0.94$. Last but not least, the time series of the estimated and experimental overall sound pressure levels, OASPL, for the Kamruzzaman+Goody and Lee+Goody models were compared. As with the spectral analysis, the Kamruzzaman+Goody model overestimated the OASPL observed during the measurement campaign. The best results with the least errors were achieved for the Lee+Goody model. Finally, the dependence of wind turbine noise on wind speed was investigated, and findings were compared with the available experimental data. Similar results were also found, except for minor differences compared to those reported in Oerlemans and Schepers [244].

Chapter 9

Conclusions

This chapter provides a summary of the main achievements, together with a proposal of issues for future research and development. The results of this dissertation are summarized and the main conclusions are drawn in Section 9.1. Suggestions for future research are provided in Section 9.2.

9.1 Summary and main results

This dissertation is dedicated to addressing significant gaps in scientific knowledge, with a primary emphasis on advancing the accuracy of reproducing realistic atmospheric turbulence interactions at spatial scales directly pertinent to wind turbine operation, incorporating insights from atmospheric physics. Moreover, it seeks to seamlessly integrate the influences of atmospheric stability into the comprehensive modeling of aerodynamics and aeroacoustics for full-scale wind turbines operating under real-world atmospheric conditions, introducing a novel methodology designed to meticulously address the unsteady and non-uniform variations in incoming wind velocity and local angle of attack seen by the wind turbine blades. This research makes a substantial contribution to the progression of wind energy deployment by acknowledging the crucial role of noise emissions from wind turbines as a potential limiting factor.

In pursuit of these objectives, this dissertation has concentrated on both aerodynamic and aeroacoustic modeling of real-scale wind turbines by making use of different research codes, the Weather Research and Forecasting (WRF) model and large-eddy simulation (LES) for mesoscale-microscale coupled high-resolution atmospheric boundary layer (ABL) simulations (WRF-LES), and an in-house Python code developed at the von Karman Institute for Fluid Dynamics, called the Broadband and Tonal Models for Airfoil Noise (BATMAN) code, which is based on a Reynolds-Averaged Navier-Stokes (RANS) and on the Amiet model for trailing-edge noise modeling. To that end, two wind turbine parameterization schemes, namely generalized actuator disk (GAD) and generalized actuator line (GAL), were implemented into the WRF-LES framework. Before the application of these

wind turbine parameterizations to real-world conditions, the so-called WRF-LES-GAD (or WLGD) and WRF-LES-GAL (or WLGL) models were verified and validated with both numerical and experimental data from the literature. The validation has included idealized simulations of a single wind turbine subject to uniform and steady inflow, as well as non-uniform and turbulent flow under varying atmospheric conditions. The performance of the WLGD model to analyze the interaction between multiple wind turbines operating in neutral ABL flow conditions was also tested. Unlike the standard wind turbine parameterization schemes used in many CFD codes, which require an offline mesoscale-microscale coupling strategy, the current WLGD and WLGL models incorporate realistic atmospheric physics and forcing, using an online method for atmospheric turbulence generation in modeling flow-wind turbine interaction. Hence, there is no need for a precursor ABL simulation generated offline by another model, as the WRF model can generate atmospheric turbulence by running it for several hours using a domain nesting strategy. Additionally, the Cell Perturbation Method (CPM), a stochastic turbulence generation algorithm previously introduced for developing atmospheric turbulence on microscale LES domains within coupled mesoscale-microscale ABL simulations, has been integrated into the WRF-LES framework. This was essential because the CPM is not available in the community version of the standard WRF model.

As a first step, an in-depth statistical analysis of turbulent wind fields was performed to analyze the ability of the CPM to reproduce turbulent flow characteristics in a vertical plane covering a real-scale wind turbine rotor. For that reason, neutral ABL flow conditions with weak, moderate, and strong large-scale forcings, corresponding to $U_g = 10, 15,$ and 20 m s^{-1} , respectively, were analyzed. The statistical characteristics of turbulent wind fields, including one-point first-order statistics based on time series, one-point second-order statistics (e.g., variance and covariance of velocity components and potential temperature, turbulence intensities, etc.), two-point second-order statistics (e.g., autocovariance for each time series, spectra and cross-spectra of velocity components and potential temperature, coherence), as well as third- and forth-order moments (e.g., skewness and kurtosis) were compared with results from the reference wind fields generated using the standard LES technique within the WRF model. Twelve simulations (three reference simulations and nine WRF-LES-CPM simulations) were performed to simulate one-hour time series of idealized neutral ABL flows in flat terrain (using periodic boundary conditions). In order to compare different realizations of each large-scale forcings, each case was repeated three times, yielding nine different wind field simulations in total. Overall, turbulent wind fields generated using WRF-LES-CPM were found to reproduce statistical properties of neutral ABL flows consistent with results from reference cases generated by the public WRF-LES model. These findings statistically demonstrate the capability of the already available CPM model in generating atmospheric turbulence on microscale LES domains, which helps reduce the fetch required to develop fine-scale turbulent structures before the flow reaches the rotor plane in multi-scale ABL simulations of wind energy applications.

The ability of the WLGD and WLGL models to reproduce the wake behavior and wake

turbulence characteristics of the NREL 5MW reference wind turbine, subject to laminar and uniform wind flow, was thoroughly evaluated in neutral atmospheric conditions. Qualitatively and quantitatively, the results from the proposed wind turbine models were compared with results from other LES codes using the generalized actuator line model. Radial distributions of time- and blade-averaged (or disk-averaged) local angle of attack, longitudinal velocity component, and nondimensional lift and drag forces were found to match the reference data accurately, except for minor differences observed in longitudinal velocity distribution along the blade, which were caused by the utilization of different strategies in the generalized actuator line model. In addition, a comparison of color maps and vertical profiles of longitudinal velocity and longitudinal component of the Reynolds stress tensor revealed that far field wake characteristics of the wind turbine largely depend on numerical discretization schemes employed by all LES research codes, as noticeable differences were found approximately after seven rotor diameter downstream of the wind turbine. The discrepancy in the far wake predictions was attributed to a faster transition to turbulence in LES codes based on higher-order numerical schemes.

A comprehensive sensitivity analysis for selection of wind turbine model parameters, based on aerodynamic force smearing function, both Gaussian and polynomial, regularization kernel width, ϵ , and 3D airfoil correction algorithm, were done. In this case, the same inflow conditions described for the simulation of the NREL 5MW wind turbine were considered. The estimates of power and thrust were found to be independent of the utilization of either a Gaussian-type force-smearing function or a polynomial function designed to provide a similar accuracy to that of the Gaussian function. Although this polynomial function was proposed as an alternative to the Gaussian force smearing function because of its, a priori, lower computational cost [252], no difference was found in this aspect. This may be due to the simulation of a single wind turbine, which does not require computationally expensive resources; hence, the discrepancy may be more pronounced when simulating wind turbine clusters in large wind farms. On the other hand, the selection of the appropriate value of ϵ is essential, as it has a significant influence on the force distribution in the rotor plane, and thus the power and thrust, as well as radial velocity distributions. It also plays a significant role in the transition to turbulence within the wake region. This is because the magnitude of the aerodynamic load projected onto the computational domain, and consequently, the shape of the wake centerline, is determined by the value of the parameter ϵ .

While it is recommended to include blade root/tip corrections to ensure the reproduction of realistic distributions of aerodynamic loads, especially near the blade tip, the accuracy of having additional corrections, such as three-dimensional correction for airfoil aerodynamic coefficients [46, 85, 195, 309], can be questioned as these empirical models are derived from certain experimental data and may not be widely applicable for all airfoils and in some specific conditions.

A validation analysis based on a comparison of power production of the Lillgrund offshore wind farm, consisting of 48 Siemens 2.3 MW wind turbines, was carried out using the

WLGD model. The WLGL model was not tested in this case because the horizontal grid resolution used in this work, which is $\Delta x = \Delta y = 10$ m, is too coarse for the WLGL model. Using relatively coarse grid resolutions in the WLGL model will result in numerical instability, and therefore cause the simulation to blow up due to the abrupt application of force along a rotating line representing the wind turbine blade. While the predicted power generation is in line with experimental data, demonstrating the feasibility and ability of the WLGD model to evaluate the aerodynamic performance of an entire wind farm, a critical finding of this study is that the distance between the wind turbines, in this case study, is insufficient to dissipate the wakes before they reach other wind turbines. This implies that when winds blow at moderate speeds and are perpendicular to the wind turbine lines (e.g., with an average wind direction of $\bar{\beta} = 120^\circ \pm 2.5^\circ$ at hub height in this study), the power production of the entire wind farm will be significantly lower than its installed power capacity. This makes the Lillgrund wind farm less aerodynamically efficient compared to less densely populated wind farms, such as the Horns Rev wind farm [239].

The third study of the WLGD and WLGL models dealt with assessing the wake behavior and aerodynamic performance of the Vestas V27 wind turbine under varying atmospheric conditions. To this end, neutral, unstable, and stable ABL conditions observed during the SWiFT field campaign were simulated. Results from the WLGD and WLGL models, including the aerodynamic effects of the nacelle and tower, were in good agreement with other LES codes and measurement data, in all atmospheric conditions analyzed. No significant discrepancies were found between the WLGD and WLGL models, even though the WLGL model applies the aerodynamic forces along the rotating blades rather than over the entire disk as in the WLGD model. Detailed, small-scale flow features, such as root and tip vortices, were not captured by the WLGL model, as the main focus was placed on comparing the two models at a relatively coarse grid resolution. Therefore, the advantages of the WLGL model over the WLGD model were not evident in the simulations.

After validating the WLGD and WLGL models against reference data reported in the literature, the WLGL model was further tested in real-world wind energy applications, and the performance of two different wind turbines was evaluated for different atmospheric stability conditions observed during field campaigns at the Perdigão and Høvsøre test sites. 1-hour simulations of three atmospheric stability case studies, which are neutral (measurement period on 09/05/2017 between 22:00-23:00 (UTC)), unstable (measurement period on 28/05/2017 between 16:00-17:00 (UTC)), and stable (measurement period on 09/05/2017 between 04:00-05:00 (UTC)), were carried out using five nested domains (two mesoscale and three microscale domains), using one-way nesting technique. 1 h time series of modeled horizontal wind speed, wind direction, potential temperature gradient, and the Obukhov length, as well as the time-averaged vertical profiles of horizontal wind speed, wind direction, potential temperature, and turbulence intensity, sampled at ~ 133 Hz at three different meteorological masts located on top of the ridges and in the valley, were compared with the experimental data sampled at 20 Hz. The modeled time series

were subsampled at 20 Hz in order to compare the numerical results and experimental data directly. Overall, WRF-LES model estimates were found to be quite satisfactory compared to experimental data at different tower locations, despite minor differences in wind speed and potential temperature gradient. In all the stability conditions tested, the best match was found in wind direction estimates, which is probably due to the fact that the prevailing wind direction in Perdigão Valley does not change significantly throughout long periods, as reported in Fernando et al. [97]. Vertical wind speed profiles on the ridges and wind direction in the valley overestimated the field data for the respective periods, but overall quite good results were obtained. This also portrays the challenges in modeling ABL flow in complex terrain due to interactions between topography features and ABL flow.

The quality of predicted spectra and cross-spectra of various quantities indicates that the current WLGL setup is a promising approach for capturing unsteady turbulent flow structures relevant for the wind turbine loading and wake characteristics.

The aerodynamic behavior of the wind turbine is also quite consistent with the power and thrust data, since the relative errors concerning power and thrust curves reported in the literature [54] are about 11% and 3%, respectively.

Another objective of this dissertation is to utilize specific aerodynamic parameters estimated by the WLGL model, such as angles of attack and relative velocities (or Reynolds number) seen by the wind turbine blades, in the near-field noise estimation for a full-scale wind turbine operating under realistic atmospheric turbulence conditions. An innovation outlined in this dissertation is that the aerodynamic quantities predicted by the WLGL model for unsteady, non-uniform, and realistic ABL flow conditions are incorporated into an aeroacoustic solver using an explicit coupling strategy. This enables full-size wind turbine noise estimation that takes into account the unsteadiness and non-uniformity of the ABL flow and provides more accurate noise estimates than standard noise modeling approaches that use time-averaged wind speed to estimate wind turbine noise. Within the scope of the literature review in this dissertation, this is the first explicit coupling strategy that combines an NWP model with a RANS-based aeroacoustic solver to account for various atmospheric scales and atmospheric physics in realistic wind turbine noise modeling based on Amiet's model for trailing-edge noise.

Prior to the in-depth analysis of full-scale wind turbine noise, ABL flow conditions were validated against data collected from the 116.5 m Høvsøre meteorological mast. The optimum computational set-up was determined through a sensitivity analysis of two reanalysis datasets and four different PBL schemes. Since there is no experimental data of the wind turbine wake behavior and aerodynamic performance, the model results were examined qualitatively. Among the two reanalysis datasets (ERA5 and GFS) and the four PBL schemes (MYNN, MYJ, QNSE, and S-H), comparably similar errors to those obtained using the GFS dataset were observed when utilizing the ERA5 reanalysis dataset in combination with the S-H PBL scheme in mesoscale ABL flow simulations at the Høvsøre test

site.

For noise modeling, a series of RANS simulations were performed for the NACA 0012 airfoil. The objective was to determine the optimum mesh configuration for subsequent noise calculations. After determining the optimum mesh configuration based on the flow analysis around the NACA 0012 airfoil, the same computational set-up was applied to the NACA 63(3)218 airfoil, which makes up the final 30% of the Siemens 2.3 MW wind turbine blade. The comparison of the computational results to the available numerical and experimental data for isolated NACA 0012 and NACA 63(3)218 airfoils, and full-scale Siemens wind turbines, has been quite satisfactory. It was also found that the proposed approach improved the previous trailing-edge noise predictions [17, 340], which were based on time-averaged uniform inflow conditions in the rotor plane at low frequencies, since non-uniformities in wind speed result in variation of the angle of attack and relative velocity seen by the blades in the rotor plane. The variations in the angle of attack and relative velocity lead to changes in the properties of the turbulent boundary layer formed near the trailing edge on the suction side, affecting the low-frequency spectral content in the sound pressure level spectrum rather than the high-frequency content, which is dominated by turbulent boundary layer flow on the pressure side.

9.2 Recommendations for future research and possible improvements

Including the GAD (or WLGD) and GAL (or WLGL) models in a multi-scale atmospheric flow solver (e.g., WRF-LES) to perform high-fidelity simulations of wind turbine dynamics, could provide an option for direct comparison of the fidelity of the predictions of the wake effects and power generation of a wind farm, between a wind turbine parameterization (WTP), like the WLGD or WLGL model and a wind farm parameterization (WFP). For example, one can use a WFP in order to investigate the wake effects of multiple wind farms on local meteorology at very coarse resolutions in mesoscale, whereas the WLGD model can be used to model individual wind turbines in an operational wind farm, to analyze the wake effects on downstream turbines and power variation over time, at relatively coarse resolutions in microscale.

It is suggested to use the WLGL model when focusing more on the flow features in the near wake region, such as the vortical structures produced by individual blades, rather than investigating the interaction between two wind farms since the WLGL model requires a finer spatial resolution and smaller time step.

Given the benefits of the WRF-LES model combined with an appropriate WTP, the WRF-LES-WTP framework may be suitable for overcoming major challenges in the design and certification process of systems operating in ABL. Moreover, considering the shortcomings of idealized set-ups of microscale WT simulations, which do not inherently involve forcing from synoptic scale weather and complex atmospheric physics, the WRF-LES-WTP

framework can help reduce the risks of making wrong decisions in wind turbine siting in complex terrain, the uncertainties in modeling realistic wake/turbulence interactions and the computational cost compared to fully resolved wind turbine simulations.

In order to realize the goal of using this approach as an additional tool in the analysis of systems in service, the parameters affecting the accuracy of the simulation (e.g., grid resolution, selection of an appropriate wind turbine parameterization, and aerodynamic force smearing kernel width, nesting strategy, and turbulence precursor) must be properly addressed. Furthermore, future research using a more realistic model setup by incorporating important sources of mesoscale inflow (e.g., storms, fronts, land-sea breezes, etc.) and complete aeroelastic wind turbine models (e.g., flexible blades, nacelle and tower effects, etc.) in WRF-like models coupled with high-resolution LES can be the next challenge.

Now, the wind turbine performance analysis and certification process are based on full-scale experiments and synthetic wind field generation. In the future, mesoscale-microscale coupling with wind turbine parameterizations is likely to be used in these processes but will require more computational power and improvements in the fidelity of existing models. Application of this approach in design standards and usual design processes by the industry will require not only refinement of existing models but also “pedagogical work” with the industry.

Future works can focus on further applications of the WLGD and WLGL approaches to model wind turbines or wind farms operating in realistic atmospheric conditions, including more sophisticated inflow from mesoscale simulations in complex terrain, for different atmospheric stability conditions. These further research steps must include their validations against available numerical or experimental data.

Since the WLGL model requires relatively low computational cost compared to fully-resolved rotor calculations, it would also be interesting to use the WLGL approach to bridge the gap between aerodynamic and aeroacoustic modeling of wind turbines operating in complex terrain under real atmospheric conditions.

In addition, the WLGL model has a great potential for further research purposes, such as the far-field noise propagation of a wind turbine under varying atmospheric conditions. The atmospheric conditions, such as temperature, humidity, and wind speed, as well as topography features that affect the reflection, refraction, and absorption of sound waves, as they travel through the surrounding air, can be obtained from the WRF-LES model. These atmospheric data can be used directly as input to an atmospheric sound propagation code to investigate the diurnal effects of such atmospheric conditions on sound propagation. Enhancing the accuracy of noise curtailment loss predictions holds the potential to optimize energy yield while concurrently reducing noise exposure to nearby residences. Such precise forecasts can foster improved community relations and enhance public acceptance of wind energy projects.

Future works should also explore the effect of different physical parameterizations and

the selection of the appropriate parameters for the cell perturbation method. This is crucial to have a best-practice case set-up prior to analyzing the interaction between the atmospheric boundary layer flows and wind turbine dynamics. With this regard, the statistical analysis of turbulent wind fields in neutral ABL conditions initiated in this dissertation can be extended to non-neutral ABL conditions to gain further insight into how atmospheric turbulence for wind energy applications affects wind loads in the rotor plane.

The simulations conducted for stable ABL conditions in this dissertation revealed that the chosen spatial resolutions were insufficient for accurately representing small-scale turbulent structures. This limitation was primarily attributed to resource constraints, which necessitated the use of coarser grids incapable of resolving such fine-scale phenomena. Thereby, one possible future research can be the utilization of finer grid resolutions, in both horizontal space and vertical direction, for a better and more realistic representation of the atmospheric boundary layer.

Appendix A

Non-dimensional boundary layer parameters computed through Reynolds-Averaged Navier-Stokes (RANS) simulations

The non-dimensional boundary layer parameters acquired from the Reynolds-Averaged Navier-Stokes (RANS) simulations for the NACA63(3)218 airfoil, employed in the analysis of aeroacoustic noise for the full-scale SWT-2.3-93 wind turbine (Section 8.2.5), have been organized in tabular form (Table A.1).

Table A.1: Non-dimensional boundary layer parameters obtained from the RANS simulations for the NACA63(3)218 airfoil.

#	Side	α [°]	Re_c [—]	x/c [—]	U_e/U_∞ [—]	δ_b/c [—]	δ_d^*/c [—]	θ_m/c [—]	C_f [—]	$\tau_w/(\rho_\infty U_\infty^2)$ [—]	u_*/U_∞ [—]	β_c [—]	Π [—]
1	SS	6	3000000	0.98	0.915	0.045	0.012	0.006	0.0007	0.0003	0.017	9.746	4.582
	PS			0.98	0.866	0.030	0.004	0.003	0.003	0.001	0.033	−1.959	—
2	SS	8	3000000	0.98	0.926	0.052	0.017	0.008	0.0004	0.0002	0.013	16.961	6.833
	PS			0.98	0.869	0.028	0.003	0.002	0.003	0.001	0.034	−1.987	—
3	SS	10	3000000	0.98	0.949	0.062	0.024	0.009	0.0001	0.00006	0.008	41.108	13.106
	PS			0.98	0.879	0.026	0.003	0.002	0.003	0.001	0.036	−2.011	—
4	SS	12	3000000	0.74	1.043	0.032	0.014	0.006	0.0003	0.0002	0.012	28.387	9.968
	PS			0.98	0.940	0.095	0.006	0.005	0.003	0.001	0.037	−2.745	—
5	SS	14	3000000	0.67	1.221	0.069	0.018	0.008	0.0002	0.0002	0.013	44.055	13.796
	PS			0.98	0.837	0.011	0.002	0.001	0.004	0.001	0.038	−2.860	—
6	SS	16	3000000	0.51	1.046	0.025	0.009	0.004	0.0004	0.0002	0.015	29.382	10.225
	PS			0.98	1.106	0.042	0.003	0.003	0.004	0.002	0.048	−6.270	—
7	SS	6	3388890	0.98	0.913	0.045	0.012	0.006	0.0007	0.0003	0.018	9.432	4.476
	PS			0.98	0.864	0.030	0.004	0.003	0.003	0.001	0.032	−1.958	—
8	SS	8	3388890	0.98	0.924	0.052	0.016	0.007	0.0004	0.0002	0.013	16.374	6.660
	PS			0.98	0.867	0.027	0.003	0.002	0.003	0.001	0.034	−1.914	—
9	SS	10	3388890	0.98	0.945	0.061	0.023	0.009	0.0002	0.00007	0.008	37.488	12.241
	PS			0.98	0.876	0.025	0.003	0.002	0.003	0.001	0.036	−1.999	—
10	SS	12	3388890	0.79	1.057	0.038	0.017	0.007	0.0002	0.0001	0.011	33.410	11.242
	PS			0.98	0.875	0.019	0.002	0.002	0.004	0.001	0.037	−2.240	—

APPENDIX A. RANS BL PARAMETERS FOR THE NACA63(3)218 AIRFOIL

11	SS	14	3388890	0.69	1.162	0.101	0.018	0.009	0.0003	0.0002	0.014	46.188	14.289
	PS			0.98	0.787	0.006	0.002	0.001	0.003	0.001	0.032	-0.201	0.324
12	SS	16	3388890	0.54	1.399	0.050	0.015	0.007	0.0002	0.0002	0.015	43.495	13.666
	PS			0.98	0.761	0.004	0.0007	0.0005	0.004	0.001	0.036	-1.119	-
13	SS	4	3777780	0.98	0.908	0.033	0.009	0.005	0.001	0.0004	0.021	5.807	3.184
	PS			0.98	0.863	0.031	0.004	0.003	0.003	0.0009	0.031	-1.924	-
14	SS	6	3777780	0.98	0.912	0.044	0.012	0.006	0.0008	0.0003	0.018	9.276	4.423
	PS			0.98	0.863	0.030	0.003	0.003	0.003	0.001	0.032	-1.940	-
15	SS	8	3777780	0.98	0.922	0.051	0.016	0.007	0.0004	0.0002	0.014	15.750	6.475
	PS			0.98	0.865	0.027	0.003	0.002	0.003	0.001	0.033	-1.900	-
16	SS	10	3777780	0.98	0.941	0.059	0.022	0.009	0.0002	0.00007	0.009	35.478	11.752
	PS			0.98	0.874	0.026	0.003	0.002	0.003	0.001	0.035	-1.995	-
17	SS	12	3777780	0.78	1.063	0.014	0.018	0.009	0.0003	0.0001	0.012	45.669	14.170
	PS			0.98	0.874	0.004	0.001	0.0007	0.004	0.001	0.036	-0.784	-
18	SS	14	3777780	0.70	1.109	0.040	0.016	0.006	0.0002	0.00009	0.010	47.133	14.505
	PS			0.98	0.907	0.022	0.002	0.002	0.004	0.001	0.038	-0.353	0.190
19	SS	16	3777780	0.56	1.323	0.123	0.016	0.009	0.0003	0.0003	0.016	47.827	14.663
	PS			0.98	0.754	0.005	0.002	0.001	0.004	0.001	0.033	0.857	1.006
20	SS	4	4166670	0.98	0.908	0.033	0.009	0.005	0.0011	0.0004	0.021	5.769	3.169
	PS			0.98	0.862	0.031	0.004	0.003	0.003	0.0009	0.031	-1.867	-
21	SS	6	4166670	0.98	0.912	0.044	0.011	0.006	0.0008	0.0003	0.018	9.073	4.354
	PS			0.98	0.862	0.030	0.003	0.003	0.003	0.001	0.032	-1.926	-
22	SS	8	4166670	0.98	0.921	0.050	0.015	0.007	0.0005	0.0002	0.014	15.216	6.315
	PS			0.98	0.863	0.027	0.003	0.002	0.003	0.001	0.033	-1.871	-
23	SS	10	4166670	0.98	0.938	0.057	0.021	0.008	0.0002	0.00008	0.009	32.662	11.055
	PS			0.98	0.871	0.026	0.003	0.002	0.003	0.001	0.035	-1.967	-
24	SS	12	4166670	0.80	1.072	0.094	0.019	0.009	0.0003	0.0002	0.013	41.064	13.096
	PS			0.98	0.872	0.004	0.001	0.0007	0.004	0.001	0.037	-1.101	-
25	SS	14	4166670	0.71	1.164	0.024	0.016	0.006	0.0002	0.0001	0.012	36.653	12.039
	PS			0.98	0.914	0.028	0.002	0.002	0.004	0.002	0.040	-4.046	-
26	SS	16	4166670	0.60	1.196	0.120	0.016	0.009	0.0003	0.0002	0.016	49.556	15.055
	PS			0.98	0.826	0.009	0.002	0.001	0.003	0.001	0.034	0.826	0.989
27	SS	4	4555560	0.98	0.907	0.033	0.009	0.005	0.0011	0.0005	0.021	5.693	3.141
	PS			0.98	0.861	0.031	0.004	0.003	0.003	0.0009	0.030	-1.846	-
28	SS	6	4555560	0.98	0.911	0.044	0.011	0.006	0.0007	0.0003	0.018	9.005	4.331
	PS			0.98	0.861	0.029	0.003	0.003	0.003	0.001	0.032	-1.904	-
29	SS	8	4555560	0.98	0.919	0.049	0.014	0.007	0.0005	0.0002	0.014	14.851	6.205
	PS			0.98	0.862	0.027	0.003	0.001	0.003	0.001	0.033	-1.835	-
30	SS	10	4555560	0.98	0.936	0.057	0.020	0.008	0.0002	0.00009	0.009	31.072	10.655
	PS			0.98	0.870	0.026	0.002	0.002	0.003	0.001	0.035	-1.940	-
31	SS	12	4555560	0.82	1.059	0.063	0.019	0.009	0.0002	0.0001	0.011	45.325	14.090
	PS			0.98	0.881	0.003	0.0009	0.006	0.004	0.001	0.037	-0.822	-
42	SS	14	4555560	0.73	1.119	0.069	0.019	0.009	0.0002	0.0001	0.012	48.450	14.805
	PS			0.98	0.857	0.013	0.002	0.001	0.004	0.001	0.036	-1.833	-
33	SS	16	4555560	0.59	1.330	0.024	0.015	0.006	0.0003	0.0002	0.015	36.544	12.012
	PS			0.98	0.777	0.006	0.0009	0.0007	0.004	0.001	0.035	-1.485	-
34	SS	4	4944440	0.98	0.907	0.033	0.008	0.005	0.0011	0.0005	0.021	5.656	3.127
	PS			0.98	0.861	0.031	0.004	0.003	0.003	0.0009	0.030	-1.822	-
35	SS	6	4944440	0.98	0.911	0.043	0.011	0.006	0.0008	0.0003	0.018	8.872	4.285
	PS			0.98	0.860	0.029	0.003	0.003	0.003	0.001	0.032	-1.872	-
36	SS	8	4944440	0.98	0.919	0.049	0.014	0.007	0.0005	0.0002	0.014	14.698	6.158
	PS			0.98	0.861	0.027	0.003	0.002	0.003	0.001	0.033	-1.840	-
37	SS	10	4944440	0.98	0.934	0.057	0.020	0.008	0.0002	0.00009	0.010	29.814	10.335
	PS			0.98	0.869	0.026	0.002	0.002	0.003	0.001	0.034	-1.931	-
38	SS	12	4944440	0.80	1.051	0.020	0.013	0.005	0.0003	0.0001	0.012	22.115	8.296
	PS			0.98	0.864	0.020	0.002	0.001	0.003	0.001	0.035	-1.720	-
39	SS	14	4944440	0.72	1.118	0.136	0.017	0.009	0.0003	0.0002	0.013	49.170	14.968
	PS			0.98	0.884	0.013	0.001	0.001	0.004	0.001	0.038	-1.681	-
40	SS	16	4944440	0.59	1.251	0.034	0.014	0.006	0.0002	0.0002	0.013	46.262	14.306
	PS			0.98	0.992	0.092	0.004	0.004	0.004	0.002	0.043	-10.605	-

41	SS	2	5333330	0.98	0.904	0.037	0.007	0.004	0.0014	0.0006	0.024	3.936	2.446
	PS			0.98	0.863	0.032	0.004	0.003	0.002	0.0008	0.029	-1.705	-
42	SS	4	5333330	0.98	0.907	0.033	0.008	0.005	0.0011	0.0005	0.021	5.630	3.117
	PS			0.98	0.860	0.031	0.004	0.003	0.003	0.0009	0.030	-1.803	-
43	SS	6	5333330	0.98	0.911	0.043	0.011	0.006	0.0008	0.0003	0.018	8.908	4.296
	PS			0.98	0.860	0.029	0.004	0.003	0.003	0.001	0.032	-1.865	-
44	SS	8	5333330	0.98	0.917	0.048	0.014	0.007	0.0005	0.0002	0.015	14.420	6.073
	PS			0.98	0.861	0.028	0.003	0.002	0.003	0.001	0.033	-1.828	-
45	SS	10	5333330	0.98	0.932	0.057	0.019	0.008	0.0002	0.0001	0.010	28.660	10.039
	PS			0.98	0.868	0.026	0.002	0.002	0.003	0.001	0.034	-1.933	-
46	SS	12	5333330	0.80	0.999	0.037	0.017	0.008	0.0003	0.0001	0.012	43.297	13.620
	PS			0.98	0.923	0.174	0.007	0.007	0.003	0.001	0.035	-3.189	-
47	SS	14	5333330	0.73	1.062	0.034	0.016	0.006	0.0002	0.0001	0.010	45.583	14.150
	PS			0.98	0.893	0.052	0.003	0.002	0.003	0.001	0.036	-2.038	-
48	SS	16	5333330	0.63	1.102	0.018	0.011	0.004	0.0002	0.0001	0.010	33.171	11.182
	PS			0.98	0.917	0.021	0.002	0.002	0.003	0.001	0.038	-0.023	0.460
49	SS	2	5722220	0.98	0.904	0.037	0.007	0.004	0.0014	0.0006	0.024	3.914	2.436
	PS			0.98	0.862	0.032	0.004	0.003	0.002	0.0008	0.029	-1.714	-
50	SS	4	5722220	0.98	0.907	0.033	0.008	0.005	0.0011	0.0005	0.021	5.620	3.113
	PS			0.98	0.860	0.030	0.004	0.003	0.002	0.0009	0.030	-1.789	-
51	SS	6	5722220	0.98	0.910	0.043	0.010	0.006	0.0008	0.0003	0.018	8.805	4.262
	PS			0.98	0.859	0.028	0.003	0.002	0.003	0.001	0.031	-1.855	-
52	SS	8	5722220	0.98	0.917	0.047	0.013	0.007	0.0005	0.0002	0.015	14.226	6.014
	PS			0.98	0.860	0.027	0.003	0.002	0.003	0.001	0.033	-1.832	-
53	SS	10	5722220	0.98	0.931	0.057	0.019	0.008	0.0002	0.0001	0.010	28.262	9.936
	PS			0.98	0.867	0.026	0.002	0.002	0.003	0.001	0.034	-1.930	-
54	SS	12	5722220	0.81	1.039	0.134	0.018	0.010	0.0003	0.0001	0.012	48.386	14.790
	PS			0.98	0.860	0.018	0.002	0.001	0.003	0.001	0.035	-1.721	-
55	SS	14	5722220	0.74	1.127	0.114	0.018	0.009	0.0002	0.0002	0.012	49.600	15.065
	PS			0.98	0.879	0.0025	0.0067	0.0005	0.004	0.001	0.038	-0.809	-
56	SS	16	5722220	0.60	1.211	0.032	0.014	0.005	0.0002	0.0001	0.012	49.500	15.043
	PS			0.98	1.010	0.093	0.005	0.002	0.004	0.002	0.043	-12.006	-
57	SS	2	6111110	0.98	0.904	0.037	0.007	0.004	0.0014	0.0006	0.024	3.919	2.438
	PS			0.98	0.862	0.032	0.004	0.003	0.002	0.0008	0.029	-1.712	-
58	SS	4	6111110	0.98	0.906	0.033	0.008	0.005	0.0001	0.0005	0.021	5.595	3.103
	PS			0.98	0.859	0.030	0.004	0.003	0.002	0.0009	0.030	-1.771	-
59	SS	6	6111110	0.98	0.909	0.042	0.010	0.006	0.0008	0.0003	0.018	8.783	4.255
	PS			0.98	0.859	0.029	0.003	0.002	0.003	0.001	0.031	-1.846	-
60	SS	8	6111110	0.98	0.916	0.047	0.013	0.007	0.0005	0.0002	0.015	14.051	5.960
	PS			0.98	0.860	0.026	0.003	0.002	0.003	0.001	0.032	-1.803	-
61	SS	10	6111110	0.98	0.929	0.054	0.018	0.008	0.0002	0.0001	0.010	27.032	9.615
	PS			0.98	0.865	0.026	0.002	0.002	0.003	0.001	0.034	-1.921	-
62	SS	12	6111110	0.85	1.017	0.050	0.019	0.008	0.0002	0.0001	0.010	40.617	12.990
	PS			0.98	0.875	0.024	0.002	0.002	0.003	0.001	0.035	-1.888	-
63	SS	14	6111110	0.73	1.065	0.038	0.015	0.007	0.0002	0.0001	0.012	44.595	13.921
	PS			0.98	0.935	0.022	0.003	0.002	0.003	0.0014	0.037	-1.240	-
64	SS	16	6111110	0.63	1.259	0.096	0.017	0.009	0.0003	0.0002	0.016	45.648	14.165
	PS			0.98	0.785	0.007	0.001	0.0007	0.004	0.001	0.034	-1.233	-
65	SS	4	6500000	0.98	0.906	0.033	0.008	0.005	0.0001	0.0005	0.021	5.558	3.089
	PS			0.98	0.859	0.031	0.004	0.003	0.002	0.0009	0.030	-1.785	-
66	SS	6	6500000	0.98	0.909	0.042	0.010	0.006	0.0008	0.0003	0.018	8.720	4.233
	PS			0.98	0.858	0.029	0.003	0.002	0.003	0.001	0.031	-1.843	-
67	SS	8	6500000	0.98	0.916	0.047	0.013	0.007	0.0005	0.0002	0.015	13.968	5.935
	PS			0.98	0.859	0.026	0.003	0.002	0.003	0.001	0.032	-1.803	-
68	SS	10	6500000	0.98	0.929	0.054	0.018	0.008	0.0002	0.0001	0.010	26.954	9.595
	PS			0.98	0.865	0.027	0.003	0.002	0.003	0.001	0.033	-1.918	-
69	SS	12	3000000	0.83	1.033	0.036	0.018	0.008	0.0002	0.0001	0.011	43.781	13.733
	PS			0.98	0.858	0.003	0.0008	0.0005	0.003	0.001	0.035	-0.709	-
70	SS	14	6500000	0.75	1.118	0.043	0.018	0.008	0.0002	0.0001	0.012	49.153	14.964
	PS			0.98	0.889	0.011	0.001	0.001	0.004	0.001	0.038	-2.007	-

APPENDIX A. RANS BL PARAMETERS FOR THE NACA63(3)218 AIRFOIL

71	SS	16	6500000	0.61	1.201	0.031	0.013	0.005	0.0002	0.0002	0.013	41.854	13.282
	PS			0.98	1.020	0.093	0.005	0.0044	0.0035	0.002	0.043	-11.609	-

Appendix B

Wind turbine properties

B.1 Vestas V27

The data used for the Vestas V27 wind turbine are given below.

Rotor speed range: 16.6-43.7 RPM

$V_{\text{cut-in}}$: 3 m s^{-1}

$V_{\text{cut-out}}$: 25 m s^{-1}

P_R : 0.225 MW

Number of blades, N_b : 3

Rotor orientation: upwind

Rotor rotation direction (as viewed from upwind): clockwise

r_{tip} : 13.5 m

r_{hub} : 0.5 m

Overhang (horizontal distance between yaw axis and rotor center): 1.88 m

Low-speed shaft tilt up angle, δ : 4.05°

D_{tow} : 1.9 m

z_{hub} : 32.1 m

Gearbox ratio: 27.565:1

Gearbox efficiency: 100%

Generator efficiency: 94.4%

Table B.1: Rotor power output, P_r , the Vestas V27 wind turbine as a function of freestream wind speed, U_∞ .

U_∞ [m s ⁻¹]	P_r [W]
3.00	0.000
4.00	3.520×10^3
5.00	1.500×10^4
6.00	3.300×10^4
7.00	5.500×10^4
8.00	8.200×10^4
9.00	1.150×10^5
10.00	1.500×10^5
11.00	1.800×10^5
12.00	2.080×10^5
13.00	2.180×10^5
14.00	2.240×10^4
15.00	2.250×10^5

Table B.2: Blade chord, twist and airfoil distribution of the Vestas V27 wind turbine.

Radius, r [m]	Chord, c [m]	Twist, θ_s [°]	Airfoil type
0.75	14.068	0.5440	Cylinder 1
1.00	13.700	0.6940	NACA 63-235
1.50	12.966	0.9934	NACA 63-235
2.00	12.245	1.2815	NACA 63-235
2.50	11.523	1.2467	NACA 63-235
3.00	10.811	1.2119	NACA 63-235
3.50	10.106	1.1770	NACA 63-224
4.00	9.409	1.1421	NACA 63-224
4.50	8.708	1.1069	NACA 63-224
5.00	8.008	1.0715	NACA 63-224
5.50	7.318	1.0362	NACA 63-224
6.00	6.658	1.0008	NACA 63-224
6.50	6.061	0.9654	NACA 63-224
7.00	5.486	0.9301	NACA 63-224
7.50	4.930	0.8949	NACA 63-224
8.00	4.393	0.8596	NACA 63-224
8.50	3.884	0.8243	NACA 63-218
9.00	3.400	0.7889	NACA 63-218
9.50	2.943	0.7534	NACA 63-218
10.00	2.514	0.7177	NACA 63-218
10.50	2.117	0.6818	NACA 63-218
11.00	1.745	0.6457	NACA 63-218
11.50	1.393	0.6095	NACA 63-218
12.00	1.063	0.5732	NACA 63-218
12.50	0.757	0.5366	NACA 63-214
13.00	0.485	0.4999	NACA 63-214
13.25	0.350	0.4816	NACA 63-214

B.2 Generic SWT-2.3-93

The data used for the generic SWT-2.3-93 wind turbine are given below. Note that these data are taken from Churchfield [54].

Rotor speed range: 6-16 RPM

$V_{\text{cut-in}}$: 4 m s⁻¹

V_R : 11 m s⁻¹

$V_{\text{cut-out}}$: 25 m s⁻¹

P_R : 2.3 MW

Region 2 tip-speed ratio, TSR : 8.4

Number of blades, N_b : 3

Rotor orientation: upwind

Rotor rotation direction (as viewed from upwind): clockwise

r_{tip} : 46.5 m

r_{hub} : 1.5 m

Overhang (horizontal distance between yaw axis and rotor apex): 4.0 m

Low-speed shaft tilt up angle, δ : 6°

Rotor forward coning angle, β : 2.5°

z_{hub} : 80.0 m

Gearbox ratio: 91:1

Gearbox efficiency: 100%

Generator efficiency: 100%

Moment of inertia about the axis of rotation, I :

I_{gen} : 0.1374×10^3 kg m²

I_{hub} : 48.87×10^3 kg m²

I_{blade} : 2.726×10^6 kg m²

Cut-in generator speed: 546 RPM

Rated generator speed: 1456 RPM

Beginning of Region 2 generator speed: 710 RPM

End of Region 2 generator speed: 1441 RPM

Cut-in generator torque: 0 N m

Rated generator torque: 15084.74 N m

Maximum rate of change of generator torque control: 5000 N m s⁻¹

Generator gain parameter, K_{gen} : 0.0045619 N m RPM⁻²

Table B.3: Rotor power, P_r , and generator power, P_g , as well as thrust, T , outputs of the generic SWT-2.3-93 wind turbine as a function of freestream wind speed, U_∞ [54].

U_∞ [m s ⁻¹]	P_r [W]	P_g [W]	T [N]
0.00	0.000	0.000	0.000
0.25	2.991×10^1	0.000	1.978×10^2
0.50	2.330×10^2	0.000	7.852×10^2
0.75	7.812×10^2	0.000	1.761×10^3
1.00	1.852×10^3	0.000	3.131×10^3
1.25	3.616×10^3	0.000	4.893×10^3
1.50	6.242×10^3	0.000	7.043×10^3
1.75	9.910×10^3	0.000	9.586×10^3
2.00	1.480×10^4	0.000	1.252×10^4
2.25	2.106×10^4	0.000	1.585×10^4
2.50	2.888×10^4	0.000	1.956×10^4
2.75	3.845×10^4	0.000	2.367×10^4
3.00	4.991×10^4	0.000	2.817×10^4
3.25	6.345×10^4	0.000	3.306×10^4
3.50	7.925×10^4	2.784×10^3	3.834×10^4
3.75	9.748×10^4	3.691×10^4	4.401×10^4
4.00	1.183×10^5	7.554×10^4	5.007×10^4
4.25	1.419×10^5	1.187×10^5	5.653×10^4
4.50	1.684×10^5	1.661×10^5	6.338×10^4
4.75	1.981×10^5	1.981×10^5	7.061×10^4
5.00	2.310×10^5	2.310×10^5	7.824×10^4
5.25	2.674×10^5	2.674×10^5	8.626×10^4
5.50	3.075×10^5	3.075×10^5	9.467×10^4
5.75	3.513×10^5	3.513×10^5	1.035×10^5
6.00	3.992×10^5	3.992×10^5	1.127×10^5
6.25	4.512×10^5	4.512×10^5	1.223×10^5
6.50	5.075×10^5	5.075×10^5	1.322×10^5
6.75	5.684×10^5	5.684×10^5	1.426×10^5
7.00	6.339×10^5	6.339×10^5	1.534×10^5
7.25	7.043×10^5	7.042×10^5	1.645×10^5
7.50	7.796×10^5	7.796×10^5	1.760×10^5
7.75	8.603×10^5	8.602×10^5	1.880×10^5
8.00	9.462×10^5	9.462×10^5	2.003×10^5
8.25	1.038×10^6	1.038×10^6	2.130×10^5
8.50	1.135×10^6	1.135×10^6	2.261×10^5
8.75	1.238×10^6	1.238×10^6	2.396×10^5
9.00	1.347×10^6	1.347×10^6	2.535×10^5
9.25	1.462×10^6	1.470×10^6	2.665×10^5
9.50	1.581×10^6	1.610×10^6	2.762×10^5
9.75	1.702×10^6	1.744×10^6	2.857×10^5
10.00	1.828×10^6	1.872×10^6	2.952×10^5
10.25	1.955×10^6	1.995×10^6	3.044×10^5
10.50	2.083×10^6	2.112×10^6	3.133×10^5
10.75	2.213×10^6	2.225×10^6	3.219×10^5
11.00	2.344×10^6	2.333×10^6	3.303×10^5

Table B.4: Blade chord, twist and airfoil distribution of the generic SWT-2.3-93 wind turbine [54].

Radius, r [m]	Chord, c [m]	Twist, θ_s [°]	Airfoil type
2.5714	2.036	9.000	Cylinder 1
4.7143	2.065	9.000	Cylinder 2
6.8571	2.334	9.000	Cylinder 2
9.0000	2.736	9.000	FFA W3-301
11.1429	3.137	9.000	FFA W3-301
13.2857	3.485	9.000	FFA W3-301
15.4286	3.372	9.000	FFA W3-301
17.5714	3.183	9.000	FFA W3-301
19.7143	2.995	8.079	FFA W3-241
21.8571	2.807	6.014	FFA W3-241
24.0000	2.618	4.231	FFA W3-241
26.1429	2.430	2.589	FFA W3-211
28.2857	2.242	1.303	FFA W3-211
30.4286	2.054	0.281	NACA 63-221
32.5714	1.865	0.594	NACA 63-221
34.7143	1.677	−1.303	NACA 63-218
36.8571	1.489	−1.840	NACA 63-218
39.0000	1.300	−2.274	NACA 63-218
41.1429	1.112	−2.627	NACA 63-218
43.2857	0.924	−2.842	NACA 63-218
45.4286	0.735	−2.973	NACA 63-218

B.3 Generic Vestas V80 2MW

The data used for the generic Vestas V80 2 MW wind turbine are given below. Note that these data are taken from Churchfield [54].

Rotor speed range: 10.8-19.1 RPM

$V_{\text{cut-in}}$: 4 m s⁻¹

V_R : 11.7 m s⁻¹

$V_{\text{cut-out}}$: 25 m s⁻¹

P_R : 2.0 MW

Region 2 tip-speed ratio, TSR : 8.4

Number of blades, N_b : 3

Rotor orientation: upwind

Rotor rotation direction (as viewed from upwind): clockwise

r_{tip} : 40.0 m

r_{hub} : 1.65 m

Overhang (horizontal distance between yaw axis and rotor apex): 4.44 m

Low-speed shaft tilt up angle, δ : 6°

Rotor forward coning angle, β : 2.0°

z_{hub} : 80.0 m

Gearbox ratio: 100:1

Gearbox efficiency: 96.5%

Generator efficiency: 96.5%

Moment of inertia about the axis of rotation, I :

I_{gen} : 0.0786×10^3 kg m²

I_{hub} : 38.92×10^3 kg m²

I_{blade} : 1.383×10^6 kg m²

Cut-in generator speed: 1080 RPM

Rated generator speed: 1910 RPM

Beginning of Region 2 generator speed: 1080 RPM

End of Region 2 generator speed: 1908 RPM

Cut-in generator torque: 200 N m

Rated generator torque: 10362.0 N m

Maximum rate of change of generator torque control: 2000 N m s⁻¹

Generator gain parameter, K_{gen} : 0.0016378 N m RPM⁻²

Table B.5: Rotor power, P_r , and generator power, P_g , as well as thrust, T , outputs of the generic Vestas V80 wind turbine as a function of wind speed, U_∞ [54].

U_∞ [m s ⁻¹]	P_r [W]	P_g [W]	T [N]
0.00	—	0.000	—
0.27	—	0.000	—
0.53	—	0.000	—
0.80	—	0.000	—
1.06	—	0.000	—
1.33	—	0.000	—
1.60	—	0.000	—
1.86	—	0.000	—
2.13	—	0.000	—
2.39	—	0.000	—
2.66	—	0.000	—
2.92	—	0.000	—
3.19	—	0.000	—
3.46	—	0.000	—
3.72	—	0.000	—
3.99	—	0.000	—
4.25	—	6.518×10^4	—
4.52	1.275×10^5	1.053×10^5	5.394×10^4
4.79	1.554×10^5	1.409×10^5	5.851×10^4
5.05	1.848×10^5	1.728×10^5	6.311×10^4
5.32	2.159×10^5	2.015×10^5	6.768×10^4
5.58	2.496×10^5	2.324×10^5	7.400×10^4
5.85	2.870×10^5	2.672×10^5	8.121×10^4
6.12	3.279×10^5	3.053×10^5	8.877×10^4
6.38	4.726×10^5	3.469×10^5	9.665×10^4
6.65	4.211×10^5	3.921×10^5	1.049×10^5
6.91	4.737×10^5	4.411×10^5	1.134×10^5
7.18	5.305×10^5	4.940×10^5	1.223×10^5
7.45	5.916×10^5	5.509×10^5	1.316×10^5
7.71	6.573×10^5	6.120×10^5	1.411×10^5
7.98	7.276×10^5	6.776×10^5	1.510×10^5
8.24	8.028×10^5	7.476×10^5	1.613×10^5
8.51	8.831×10^5	8.223×10^5	1.718×10^5
8.77	9.685×10^5	9.019×10^5	1.827×10^5
9.04	1.059×10^6	9.863×10^5	1.940×10^5
9.31	1.155×10^6	1.076×10^6	2.056×10^5
9.57	1.258×10^6	1.172×10^6	2.164×10^5
9.84	1.363×10^6	1.276×10^6	2.234×10^5
10.10	1.469×10^6	1.379×10^6	2.305×10^5
10.37	1.575×10^6	1.483×10^6	2.375×10^5
10.64	1.680×10^6	1.586×10^6	2.446×10^5
10.90	1.786×10^6	1.690×10^6	2.517×10^5
11.17	1.892×10^6	1.793×10^6	2.587×10^5
11.43	1.997×10^6	1.897×10^6	2.658×10^5
11.70	2.103×10^6	2.000×10^6	2.728×10^5

Table B.6: Blade chord, twist and airfoil distribution of the generic Vestas V80 wind turbine [54].

Radius, r [m]	Chord, c [m]	Twist, θ_s [°]	Airfoil type
2.5631	2.004	9.500	Cylinder 1
4.3893	2.523	9.500	Cylinder 2
6.2155	3.015	9.500	FFA W3-301
8.0417	3.278	9.500	FFA W3-301
9.8679	3.309	9.500	FFA W3-301
11.6940	3.195	9.500	FFA W3-301
15.5202	3.039	9.218	FFA W3-241
15.3464	3.863	7.810	FFA W3-211
17.1726	3.687	6.401	FFA W3-211
18.9988	2.511	5.113	FFA W3-211
20.8250	2.334	3.828	FFA W3-211
22.6512	2.158	2.613	NACA 63-221
24.4774	1.982	1.482	NACA 63-221
26.3036	1.806	0.417	NACA 63-221
28.1298	1.630	−0.494	NACA 63-221
29.9560	1.454	−1.233	NACA 63-218
31.7821	1.278	−1.792	NACA 63-218
33.6083	1.102	−2.244	NACA 63-218
35.4345	0.926	−2.611	NACA 63-218
37.2607	0.749	−2.835	NACA 63-218
39.0869	0.573	−2.971	NACA 63-218

B.4 Aerodynamic airfoil coefficients used for the Vestas V27, generic SWT-2.3-93, and generic Vestas V80 wind turbines

While precise Mach number, M , information is unfortunately unavailable for documented aerodynamic coefficients of cylinders and airfoils, it is noteworthy that the relevant Mach numbers remain in the incompressible range ($M < 0.3$).

Cylinder 1

Table B.7: Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 0.75 \times 10^6$ for Cylinder 1 [54].

C_L [-]	C_D [-]	C_M [-]
0.000	0.500	0.000

Cylinder 2

Table B.8: Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 0.75 \times 10^6$ for Cylinder 2 [54].

C_L [-]	C_D [-]	C_M [-]
0.000	0.350	0.000

FFA W-301

Table B.9: Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 1.5 \times 10^6$ for the FFA W3-301 airfoil [19, 54].

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.1807	0.0000	40.00	0.975	0.6714	-0.1031
-170.00	0.473	0.2168	0.4000	50.00	0.836	0.8731	-0.1585
-160.00	0.946	0.3207	-0.0710	60.00	0.666	1.0578	-0.2052
-150.00	0.782	0.4790	0.0512	70.00	0.461	1.2009	-0.2457
-140.00	0.682	0.6714	0.1162	80.00	0.232	1.2825	-0.2794
-130.00	0.585	0.8731	0.1711	90.00	0.000	1.2900	-0.3044
-120.00	0.466	1.0578	0.2235	100.00	-0.162	1.2825	-0.3328
-110.00	0.323	1.2009	0.2721	110.00	-0.323	1.2009	-0.3473
-100.00	0.162	1.2825	0.3128	120.00	-0.466	1.0578	-0.3511
-90.00	0.000	1.2900	0.3406	130.00	-0.585	0.8731	-0.3514
-80.00	-0.162	1.2825	0.3690	140.00	-0.682	0.6714	-0.3609
-70.00	-0.323	1.2009	0.3834	150.00	-0.782	0.4790	-0.4070
-60.00	-0.466	1.0578	0.3873	160.00	-0.946	0.3207	-0.5701
-50.00	-0.585	0.8731	0.3876	170.00	-0.473	0.2168	-0.5000
-40.00	-0.682	0.6714	0.3971	180.00	0.000	0.1807	0.0000
-30.00	-0.782	0.4790	0.4431				
-20.00	-0.945	0.3206	0.6058				
-10.00	-0.434	0.1823	0.4542				
0.00	0.077	0.0440	0.0181				
0.57	0.151	0.0361	0.0363				
1.60	0.286	0.0316	0.0526				
2.64	0.431	0.0296	0.0667				
3.67	0.568	0.0288	0.0777				
4.71	0.705	0.0277	0.0878				
5.74	0.826	0.0287	0.0954				
6.78	0.948	0.0296	0.1009				
7.81	1.064	0.0331	0.1061				
8.84	1.161	0.0386	0.1087				
9.88	1.217	0.0536	0.1133				
10.91	1.158	0.1000	0.1305				
11.95	1.141	0.1325	0.1391				
12.98	1.145	0.1594	0.1442				
14.02	1.178	0.1789	0.1452				
15.05	1.216	0.1983	0.1454				
16.09	1.257	0.2182	0.1442				
17.12	1.279	0.2420	0.1399				
18.15	1.293	0.2683	0.1342				
19.19	1.328	0.2954	0.1348				
20.22	1.366	0.3237	0.1367				
30.00	1.117	0.4790	-0.0256				

FFA W-241**Table B.10:** Lift, C_L , drag, C_D , and moment, C_M , coefficients for $Re = 1.5 \times 10^6$ for the FFA W3-241 airfoil [19, 54].

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.0794	0.0000	40.00	0.958	0.5938	-0.0441
-170.00	0.418	0.1171	0.4000	50.00	0.826	0.8080	-0.0985
-160.00	0.836	0.2255	-0.0142	60.00	0.661	1.0072	-0.1456
-150.00	0.762	0.3913	0.0956	70.00	0.459	1.1663	-0.1881
-140.00	0.670	0.5938	0.1577	80.00	0.231	1.2649	-0.2252
-130.00	0.578	0.8080	0.2111	90.00	0.000	1.2900	-0.2547
-120.00	0.462	1.0072	0.2637	100.00	-0.162	1.2649	-0.2788
-110.00	0.321	1.1663	0.3141	110.00	-0.321	1.1663	-0.2887
-100.00	0.162	1.2649	0.3581	120.00	-0.462	1.0072	-0.2880
-90.00	0.000	1.2900	0.3903	130.00	-0.578	0.8080	-0.2842
-80.00	-0.162	1.2649	0.4145	140.00	-0.670	0.5938	-0.2899
-70.00	-0.321	1.1663	0.4244	150.00	-0.762	0.3913	-0.3321
-60.00	-0.462	1.0072	0.4237	160.00	-0.836	0.2255	-0.4456
-50.00	-0.578	0.8080	0.4198	170.00	-0.418	0.1171	-0.5000
-40.00	-0.670	0.5938	0.4256	180.00	0.000	0.0794	0.0000
-30.00	-0.762	0.3913	0.4677				
-20.00	-0.823	0.2307	0.5750				
-10.00	-0.311	0.1244	0.3833				
0.00	0.201	0.0181	0.0678				
0.04	0.290	0.0177	0.0772				
1.16	0.416	0.0182	0.0812				
2.28	0.537	0.0195	0.0845				
3.41	0.665	0.0199	0.0884				
4.53	0.790	0.0214	0.0914				
5.66	0.914	0.0228	0.0939				
6.78	1.023	0.0243	0.0968				
7.90	1.145	0.0261	0.0991				
9.03	1.249	0.0274	0.1006				
10.15	1.337	0.0300	0.1015				
11.27	1.398	0.0302	0.1006				
12.40	1.476	0.0330	0.1009				
13.52	1.486	0.0456	0.1008				
14.65	1.555	0.0571	0.1006				
15.77	1.528	0.0853	0.1097				
16.89	1.368	0.1410	0.1386				
18.02	1.343	0.1736	0.1508				
19.14	1.366	0.1912	0.1521				
20.27	1.328	0.2181	0.1579				
21.39	1.277	0.2455	0.1581				
30.00	1.088	0.3913	0.0308				

FFA W-211**Table B.11:** Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 1.8 \times 10^6$ for the FFA W3-211 airfoil [19, 54].

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.0564	0.0000	40.00	0.951	0.5762	-0.0567
-170.00	0.436	0.0944	0.4000	50.00	0.822	0.7932	-0.1036
-160.00	0.873	0.2039	0.0438	60.00	0.659	0.9957	-0.1455
-150.00	0.755	0.3713	0.1359	70.00	0.458	1.1584	-0.1837
-140.00	0.666	0.5762	0.1889	80.00	0.231	1.2609	-0.2169
-130.00	0.575	0.7932	0.2374	90.00	0.000	1.2900	-0.2428
-120.00	0.461	0.9957	0.2862	100.00	-0.162	1.2609	-0.2614
-110.00	0.320	1.1584	0.3332	110.00	-0.320	1.1584	-0.2659
-100.00	0.162	1.2609	0.3735	120.00	-0.461	0.9957	-0.2602
-90.00	0.000	1.2900	0.4022	130.00	-0.575	0.7932	-0.2514
-80.00	-0.162	1.2609	0.4208	140.00	-0.666	0.5762	-0.2513
-70.00	-0.320	1.1584	0.4253	150.00	-0.755	0.3713	-0.2837
-60.00	-0.461	0.9957	0.4196	160.00	-0.873	0.2039	-0.4010
-50.00	-0.575	0.7932	0.4108	170.00	-0.436	0.0944	-0.5000
-40.00	-0.666	0.5762	0.4108	180.00	0.000	0.0564	0.0000
-30.00	-0.755	0.3713	0.4432	180.00	0.000	0.0564	0.0000
-20.00	-0.865	0.2066	0.5572				
-10.00	-0.312	0.1061	0.3565				
0.00	0.241	0.0056	0.0797				
0.09	0.351	0.0048	0.0834				
1.17	0.486	0.0045	0.0848				
2.25	0.620	0.0047	0.0861				
3.33	0.753	0.0053	0.0877				
4.41	0.885	0.0053	0.0881				
5.49	1.022	0.0060	0.0890				
6.58	1.144	0.0065	0.0895				
7.66	1.273	0.0069	0.0893				
8.74	1.394	0.0086	0.0876				
9.82	1.474	0.0125	0.0828				
10.90	1.509	0.0196	0.0770				
11.98	1.438	0.0605	0.0820				
13.07	1.424	0.0842	0.0881				
14.15	1.403	0.1057	0.0944				
15.23	1.379	0.1226	0.1000				
16.31	1.346	0.1356	0.1019				
17.39	1.301	0.1477	0.1032				
18.47	1.233	0.1578	0.1014				
19.56	1.282	0.1868	0.1109				
20.64	1.286	0.2130	0.1188				
30.00	1.078	0.3713	0.0048				

NACA 63-214**Table B.12:** Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 2 \times 10^6$ for the NACA 63-214 airfoil.

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.010	0.0000	-13.00	-0.912	0.031	0.0450
-175.00	0.426	0.000	0.3126	-12.00	-0.902	0.024	0.0294
-170.00	0.710	0.010	0.4000	-11.00	-0.887	0.019	0.0100
-165.00	0.865	0.043	0.3561	-10.00	-0.868	0.015	-0.0138
-160.00	0.902	0.103	0.2748	-9.50	-0.855	0.013	-0.0265
-155.00	0.846	0.189	0.2301	-9.00	-0.829	0.011	-0.0353
-150.00	0.765	0.293	0.2167	-8.50	-0.781	0.011	-0.0367
-145.00	0.718	0.407	0.2138	-8.00	-0.724	0.010	-0.0349
-140.00	0.689	0.528	0.2170	-7.50	-0.669	0.010	-0.0344
-135.00	0.652	0.653	0.2259	-7.00	-0.616	0.009	-0.0350
-130.00	0.604	0.778	0.2384	-6.50	-0.561	0.009	-0.0353
-125.00	0.550	0.900	0.2522	-6.00	-0.505	0.009	-0.0354
-120.00	0.489	1.016	0.2663	-5.50	-0.449	0.008	-0.0356
-115.00	0.420	1.120	0.2799	-5.00	-0.393	0.008	-0.0360
-110.00	0.343	1.212	0.2918	-4.50	-0.337	0.007	-0.0364
-105.00	0.260	1.286	0.3012	-4.00	-0.282	0.007	-0.0369
-100.00	0.174	1.344	0.3078	-3.50	-0.226	0.006	-0.0375
-95.00	0.087	1.383	0.3111	-3.00	-0.169	0.005	-0.0381
-90.00	0.000	1.397	0.3095	-2.50	-0.111	0.005	-0.0387
-85.00	-0.087	1.383	0.3017	-2.00	-0.052	0.005	-0.0393
-80.00	-0.174	1.344	0.2893	-1.50	0.007	0.005	-0.0399
-75.00	-0.260	1.286	0.2740	-1.00	0.065	0.005	-0.0405
-70.00	-0.343	1.212	0.2564	-0.50	0.124	0.005	-0.0410
-65.00	-0.420	1.120	0.2368	0.00	0.183	0.005	-0.0416
-60.00	-0.489	1.016	0.2161	0.50	0.241	0.005	-0.0422
-55.00	-0.551	0.900	0.1950	1.00	0.300	0.005	-0.0428
-50.00	-0.604	0.778	0.1744	1.50	0.359	0.005	-0.0434
-45.00	-0.651	0.653	0.1548	2.00	0.417	0.005	-0.0439
-40.00	-0.689	0.528	0.1370	2.50	0.475	0.005	-0.0443
-35.00	-0.721	0.407	0.1214	3.00	0.532	0.006	-0.0447
-30.00	-0.765	0.293	0.1082	3.50	0.589	0.006	-0.0451
-25.00	-0.836	0.188	0.0971	4.00	0.645	0.006	-0.0453
-21.00	-0.891	0.118	0.0890	4.50	0.697	0.007	-0.0452
-20.00	-0.902	0.103	0.0870	5.00	0.748	0.008	-0.0448
-19.00	-0.911	0.089	0.0848	5.50	0.798	0.009	-0.0444
-18.00	-0.918	0.076	0.0822	6.00	0.850	0.010	-0.0441
-17.00	-0.923	0.065	0.0787	6.50	0.903	0.010	-0.0439
-16.00	-0.925	0.055	0.0736	7.00	0.956	0.011	-0.0437
-15.00	-0.924	0.046	0.0667	7.50	1.008	0.011	-0.0435
-14.00	-0.920	0.038	0.0573	8.00	1.061	0.012	-0.0433

B.4. AERODYNAMIC AIRFOIL COEFFICIENTS FOR THE THREE WTS

α [°]	C_L [-]	C_D [-]	C_M [-]		α [°]	C_L [-]	C_D [-]	C_M [-]
8.50	1.112	0.012	-0.0430		60.00	0.699	1.016	-0.2963
9.00	1.161	0.013	-0.0423		65.00	0.599	1.120	-0.3148
9.50	1.208	0.014	-0.0411		70.00	0.490	1.212	-0.3323
10.00	1.251	0.014	-0.0395		75.00	0.373	1.286	-0.3488
10.50	1.292	0.015	-0.0374		80.00	0.249	1.344	-0.3642
11.00	1.329	0.016	-0.0350		85.00	0.119	1.383	-0.3784
11.50	1.364	0.017	-0.0323		90.00	0.000	1.397	-0.3891
12.00	1.395	0.018	-0.0293		95.00	-0.093	1.383	-0.3945
12.50	1.424	0.019	-0.0262		100.00	-0.174	1.344	-0.3953
13.00	1.448	0.021	-0.0233		105.00	-0.258	1.286	-0.3924
13.50	1.466	0.023	-0.0207		110.00	-0.343	1.212	-0.3864
14.00	1.484	0.026	-0.0182		115.00	-0.420	1.120	-0.3777
14.50	1.505	0.028	-0.0159		120.00	-0.489	1.016	-0.3672
15.00	1.522	0.031	-0.0150		125.00	-0.550	0.900	-0.3558
15.50	1.528	0.035	-0.0170		130.00	-0.604	0.778	-0.3450
16.00	1.524	0.040	-0.0217		135.00	-0.652	0.653	-0.3364
16.50	1.510	0.046	-0.0288		140.00	-0.689	0.528	-0.3305
17.00	1.488	0.052	-0.0377		145.00	-0.718	0.407	-0.3295
17.50	1.461	0.060	-0.0481		150.00	-0.765	0.293	-0.3423
18.00	1.429	0.068	-0.0595		155.00	-0.846	0.189	-0.3771
18.50	1.394	0.076	-0.0715		160.00	-0.902	0.103	-0.4339
19.00	1.358	0.085	-0.0836		165.00	-0.865	0.043	-0.4974
19.50	1.322	0.094	-0.0955		170.00	-0.710	0.010	-0.5000
20.00	1.289	0.103	-0.1066		175.00	-0.426	0.000	-0.3611
20.50	1.259	0.112	-0.1166		180.00	0.000	0.010	0.0000
21.00	1.232	0.121	-0.1256					
21.50	1.208	0.130	-0.1335					
22.00	1.188	0.139	-0.1405					
22.50	1.170	0.148	-0.1466					
23.00	1.155	0.157	-0.1519					
23.50	1.142	0.166	-0.1564					
24.00	1.131	0.175	-0.1602					
24.50	1.122	0.185	-0.1635					
25.00	1.115	0.194	-0.1662					
25.50	1.110	0.204	-0.1684					
26.00	1.105	0.213	-0.1701					
26.50	1.102	0.223	-0.1716					
27.00	1.100	0.232	-0.1727					
27.50	1.098	0.242	-0.1737					
28.00	1.097	0.252	-0.1745					
30.00	1.093	0.293	-0.1777					
35.00	1.051	0.406	-0.1956					
40.00	0.985	0.528	-0.2201					
45.00	0.925	0.653	-0.2406					
50.00	0.863	0.778	-0.2585					
55.00	0.788	0.900	-0.2772					

NACA 63-218**Table B.13:** Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 2 \times 10^6$ for the NACA 63-218 airfoil [54].

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.0100	0.0000	30.00	0.927	0.2166	-0.0505
-170.00	0.443	0.0100	0.4000	40.00	0.859	0.4393	-0.0992
-160.00	0.734	0.0360	0.0358	50.00	0.768	0.6784	-0.1418
-150.00	0.649	0.2166	0.0973	60.00	0.629	0.9064	-0.1829
-140.00	0.602	0.4393	0.1404	70.00	0.445	1.0973	-0.2223
-130.00	0.537	0.6784	0.1853	80.00	0.228	1.2299	-0.2581
-120.00	0.441	0.9064	0.2335	90.00	0.000	1.2900	-0.2879
-110.00	0.312	1.0973	0.2816	100.00	-0.160	1.2299	-0.2948
-100.00	0.160	1.2299	0.3246	110.00	-0.312	1.0973	-0.2872
-90.00	0.000	1.2900	0.3571	120.00	-0.441	0.9064	-0.2691
-80.00	-0.160	1.2299	0.3641	130.00	-0.537	0.6784	-0.2472
-70.00	-0.312	1.0973	0.3565	140.00	-0.602	0.4393	-0.2312
-60.00	-0.441	0.9064	0.3384	150.00	-0.649	0.2166	-0.2378
-50.00	-0.537	0.6784	0.3165	160.00	-0.734	0.0360	-0.3151
-40.00	-0.602	0.4393	0.3005	170.00	-0.443	0.0100	-0.5000
-30.00	-0.649	0.2166	0.3071	180.00	0.000	0.0100	0.0000
-20.00	-0.734	0.0360	0.3844				
-10.00	-0.393	0.0031	0.3303				
0.00	0.116	0.0061	0.0346				
0.16	0.177	0.0061	0.0367				
1.08	0.301	0.0059	0.0382				
1.99	0.381	0.0060	0.0397				
2.91	0.515	0.0059	0.0426				
3.82	0.618	0.0062	0.0463				
4.74	0.704	0.0067	0.0484				
5.65	0.803	0.0074	0.0504				
6.57	0.850	0.0082	0.0499				
7.48	0.944	0.0102	0.0491				
8.40	1.057	0.0120	0.0485				
9.32	1.142	0.0143	0.0500				
10.23	1.190	0.0158	0.0526				
11.15	1.229	0.0168	0.0480				
12.06	1.287	0.0179	0.0564				
12.98	1.287	0.0173	0.0601				
13.89	1.262	0.0156	0.0625				
14.81	1.236	0.0129	0.0660				
15.72	1.198	0.0090	0.0715				
16.64	1.157	0.0051	0.0751				
17.55	1.111	0.0008	0.0725				
20.00	1.048	0.0360	0.0330				

NACA 63-221

Table B.14: Lift, C_L , drag, C_D , and moment, C_M , coefficients for $\text{Re} = 3 \times 10^6$ for the NACA 63-221 airfoil [19, 54].

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.0100	0.0000	30.00	0.943	0.1926	-0.0189
-170.00	0.387	0.0100	0.4000	40.00	0.869	0.4181	-0.0760
-160.00	0.753	0.0100	-0.0041	50.00	0.773	0.6606	-0.1233
-150.00	0.660	0.1926	0.0733	60.00	0.633	0.8925	-0.1684
-140.00	0.608	0.4181	0.1212	70.00	0.447	1.0878	-0.2120
-130.00	0.541	0.6606	0.1686	80.00	0.228	1.2251	-0.2528
-120.00	0.443	0.8925	0.2194	90.00	0.000	1.2900	-0.2881
-110.00	0.313	1.0878	0.2712	100.00	-0.160	1.2251	-0.2983
-100.00	0.160	1.2251	0.3188	110.00	-0.313	1.0878	-0.2934
-90.00	0.000	1.2900	0.3569	120.00	-0.443	0.8925	-0.2777
-80.00	-0.160	1.2251	0.3670	130.00	-0.541	0.6606	-0.2584
-70.00	-0.313	1.0878	0.3621	140.00	-0.608	0.4181	-0.2462
-60.00	-0.443	0.8925	0.3465	150.00	-0.660	0.1926	-0.2607
-50.00	-0.541	0.6606	0.3272	160.00	-0.753	0.0100	-0.3598
-40.00	-0.608	0.4181	0.3150	170.00	-0.387	0.0100	-0.5000
-30.00	-0.660	0.1926	0.3294	180.00	0.000	0.0100	0.0000
-20.00	-0.753	0.0100	0.4285				
-10.00	-0.319	0.0054	0.3113				
0.00	0.137	0.0064	0.0344				
0.07	0.200	0.0064	0.0394				
1.10	0.294	0.0066	0.0418				
2.13	0.405	0.0067	0.0442				
3.16	0.525	0.0069	0.0481				
4.19	0.639	0.0070	0.0530				
5.22	0.781	0.0073	0.0557				
6.25	0.881	0.0078	0.0585				
7.28	0.962	0.0095	0.0600				
8.31	1.043	0.0112	0.0622				
9.34	1.123	0.0161	0.0630				
10.37	1.145	0.0175	0.0638				
11.40	1.153	0.0169	0.0660				
12.43	1.148	0.0160	0.0711				
13.46	1.121	0.0149	0.0764				
14.49	1.139	0.0142	0.0799				
15.52	1.131	0.0132	0.0831				
16.55	1.116	0.0117	0.0911				
17.58	1.107	0.0096	0.0936				
18.61	1.089	0.0069	0.0947				
19.64	1.085	0.0044	0.0958				
20.00	1.076	0.0100	0.0892				

NACA 63-224**Table B.15:** Lift, C_L , drag, C_D , and moment, C_M , coefficients for $Re = 2 \times 10^6$ for the NACA 63-224 airfoil.

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.0100	0.0000	-13.00	-0.903	0.0295	-0.0340
-175.00	0.358	-0.0042	0.3203	-12.00	-0.904	0.0224	-0.0401
-170.00	0.602	0.0100	0.4000	-11.00	-0.896	0.0168	-0.0410
-165.00	0.742	0.0507	0.3436	-10.00	-0.879	0.0130	-0.0359
-160.00	0.786	0.1158	0.2554	-9.50	-0.866	0.0117	-0.0311
-155.00	0.753	0.2026	0.2164	-9.00	-0.844	0.0107	-0.0267
-150.00	0.698	0.3054	0.2133	-8.50	-0.808	0.0098	-0.0243
-145.00	0.667	0.4184	0.2158	-8.00	-0.764	0.0090	-0.0234
-140.00	0.648	0.5384	0.2211	-7.50	-0.715	0.0083	-0.0231
-135.00	0.620	0.6626	0.2320	-7.00	-0.663	0.0078	-0.0231
-130.00	0.580	0.7873	0.2462	-6.50	-0.607	0.0074	-0.0236
-125.00	0.532	0.9084	0.2610	-6.00	-0.549	0.0072	-0.0243
-120.00	0.476	1.0225	0.2755	-5.50	-0.490	0.0070	-0.0252
-115.00	0.411	1.1262	0.2891	-5.00	-0.430	0.0069	-0.0262
-110.00	0.337	1.2163	0.3007	-4.50	-0.370	0.0068	-0.0273
-105.00	0.257	1.2900	0.3096	-4.00	-0.309	0.0068	-0.0284
-100.00	0.173	1.3462	0.3154	-3.50	-0.249	0.0067	-0.0295
-95.00	0.087	1.3834	0.3176	-3.00	-0.188	0.0067	-0.0306
-90.00	0.000	1.3971	0.3151	-2.50	-0.127	0.0067	-0.0317
-85.00	-0.087	1.3834	0.3069	-2.00	-0.066	0.0066	-0.0329
-80.00	-0.173	1.3462	0.2941	-1.50	-0.005	0.0066	-0.0341
-75.00	-0.257	1.2900	0.2783	-1.00	0.056	0.0066	-0.0353
-70.00	-0.337	1.2163	0.2600	-0.50	0.117	0.0066	-0.0365
-65.00	-0.411	1.1262	0.2397	0.00	0.178	0.0067	-0.0376
-60.00	-0.476	1.0225	0.2179	0.50	0.239	0.0067	-0.0388
-55.00	-0.533	0.9084	0.1953	1.00	0.300	0.0067	-0.0399
-50.00	-0.580	0.7873	0.1734	1.50	0.361	0.0068	-0.0411
-45.00	-0.618	0.6627	0.1530	2.00	0.422	0.0068	-0.0422
-40.00	-0.648	0.5384	0.1319	2.50	0.482	0.0069	-0.0433
-35.00	-0.674	0.4182	0.1099	3.00	0.542	0.0069	-0.0444
-30.00	-0.698	0.3054	0.0968	3.50	0.602	0.0070	-0.0455
-25.00	-0.725	0.2033	0.0948	4.00	0.662	0.0071	-0.0465
-21.00	-0.770	0.1320	0.0758	4.50	0.722	0.0072	-0.0475
-20.00	-0.786	0.1158	0.0654	5.00	0.781	0.0073	-0.0484
-19.00	-0.805	0.1004	0.0522	5.50	0.840	0.0075	-0.0493
-18.00	-0.826	0.0858	0.0370	6.00	0.898	0.0076	-0.0500
-17.00	-0.847	0.0722	0.0207	6.50	0.954	0.0078	-0.0505
-16.00	-0.866	0.0597	0.0045	7.00	1.009	0.0081	-0.0508
-15.00	-0.883	0.0483	-0.0108	7.50	1.062	0.0085	-0.0507
-14.00	-0.895	0.0382	-0.0239	8.00	1.110	0.0090	-0.0500

B.4. AERODYNAMIC AIRFOIL COEFFICIENTS FOR THE THREE WTS

α [°]	C_L [-]	C_D [-]	C_M [-]		α [°]	C_L [-]	C_D [-]	C_M [-]
8.50	1.151	0.0096	-0.0482		60.00	0.680	1.0225	-0.2893
9.00	1.182	0.0105	-0.0447		65.00	0.586	1.1262	-0.3086
9.50	1.199	0.0116	-0.0393		70.00	0.482	1.2163	-0.3266
10.00	1.207	0.0131	-0.0333		75.00	0.369	1.2900	-0.3434
10.50	1.215	0.0152	-0.0283		80.00	0.247	1.3462	-0.3589
11.00	1.224	0.0176	-0.0244		85.00	0.118	1.3834	-0.3728
11.50	1.237	0.0199	-0.0213		90.00	0.000	1.3971	-0.3835
12.00	1.249	0.0225	-0.0185		95.00	-0.093	1.3834	-0.3892
12.50	1.259	0.0255	-0.0159		100.00	-0.173	1.3462	-0.3905
13.00	1.265	0.0288	-0.0136		105.00	-0.255	1.2900	-0.3879
13.50	1.272	0.0324	-0.0119		110.00	-0.337	1.2163	-0.3819
14.00	1.279	0.0362	-0.0103		115.00	-0.411	1.1262	-0.3731
14.50	1.286	0.0402	-0.0088		120.00	-0.476	1.0225	-0.3621
15.00	1.291	0.0446	-0.0085		125.00	-0.532	0.9084	-0.3499
15.50	1.289	0.0497	-0.0106		130.00	-0.580	0.7873	-0.3375
16.00	1.282	0.0554	-0.0150		135.00	-0.620	0.6626	-0.3261
16.50	1.269	0.0616	-0.0213		140.00	-0.648	0.5384	-0.3177
17.00	1.253	0.0683	-0.0293		145.00	-0.667	0.4184	-0.3145
17.50	1.234	0.0755	-0.0385		150.00	-0.698	0.3054	-0.3184
18.00	1.213	0.0830	-0.0485		155.00	-0.753	0.2026	-0.3350
18.50	1.190	0.0909	-0.0590		160.00	-0.786	0.1158	-0.3838
19.00	1.167	0.0990	-0.0697		165.00	-0.742	0.0507	-0.4666
19.50	1.144	0.1073	-0.0801		170.00	-0.602	0.0100	-0.5000
20.00	1.123	0.1158	-0.0900		175.00	-0.358	-0.0042	-0.3794
20.50	1.104	0.1243	-0.0989		180.00	0.000	0.0100	0.0000
21.00	1.087	0.1330	-0.1069					
21.50	1.072	0.1417	-0.1141					
22.00	1.059	0.1505	-0.1205					
22.50	1.048	0.1594	-0.1261					
23.00	1.038	0.1683	-0.1311					
23.50	1.030	0.1774	-0.1355					
24.00	1.023	0.1866	-0.1392					
24.50	1.017	0.1959	-0.1425					
25.00	1.013	0.2052	-0.1453					
25.50	1.009	0.2147	-0.1477					
26.00	1.006	0.2243	-0.1498					
26.50	1.004	0.2340	-0.1515					
27.00	1.002	0.2439	-0.1531					
27.50	1.001	0.2538	-0.1544					
28.00	1.000	0.2639	-0.1557					
30.00	0.997	0.3054	-0.1607					
35.00	0.970	0.4177	-0.1812					
40.00	0.926	0.5384	-0.2070					
45.00	0.881	0.6628	-0.2292					
50.00	0.829	0.7873	-0.2491					
55.00	0.762	0.9083	-0.2692					

NACA 63-235**Table B.16:** Lift, C_L , drag, C_D , and moment, C_M , coefficients for $Re = 2 \times 10^6$ for the NACA 63-235 airfoil.

α [°]	C_L [-]	C_D [-]	C_M [-]	α [°]	C_L [-]	C_D [-]	C_M [-]
-180.00	0.000	0.0100	0.0000	-13.00	-0.846	0.0301	-0.0261
-175.00	0.323	-0.0035	0.3231	-12.00	-0.831	0.0235	-0.0339
-170.00	0.547	0.0100	0.4000	-11.00	-0.800	0.0185	-0.0385
-165.00	0.679	0.0494	0.3392	-10.00	-0.751	0.0152	-0.0392
-160.00	0.727	0.1135	0.2494	-9.50	-0.719	0.0142	-0.0380
-155.00	0.706	0.2002	0.2140	-9.00	-0.684	0.0135	-0.0364
-150.00	0.663	0.3033	0.2160	-8.50	-0.648	0.0128	-0.0350
-145.00	0.641	0.4165	0.2214	-8.00	-0.611	0.0121	-0.0339
-140.00	0.627	0.5366	0.2279	-7.50	-0.572	0.0114	-0.0328
-135.00	0.603	0.6609	0.2399	-7.00	-0.534	0.0108	-0.0316
-130.00	0.568	0.7857	0.2551	-6.50	-0.496	0.0103	-0.0301
-125.00	0.523	0.9070	0.2706	-6.00	-0.460	0.0099	-0.0283
-120.00	0.470	1.0213	0.2854	-5.50	-0.424	0.0096	-0.0261
-115.00	0.406	1.1252	0.2991	-5.00	-0.388	0.0094	-0.0239
-110.00	0.334	1.2155	0.3107	-4.50	-0.347	0.0092	-0.0223
-105.00	0.255	1.2893	0.3195	-4.00	-0.301	0.0091	-0.0215
-100.00	0.172	1.3458	0.3250	-3.50	-0.248	0.0090	-0.0218
-95.00	0.087	1.3833	0.3270	-3.00	-0.192	0.0090	-0.0226
-90.00	0.000	1.3971	0.3242	-2.50	-0.136	0.0089	-0.0233
-85.00	-0.087	1.3833	0.3156	-2.00	-0.082	0.0089	-0.0240
-80.00	-0.172	1.3458	0.3024	-1.50	-0.026	0.0088	-0.0247
-75.00	-0.255	1.2893	0.2861	-1.00	0.029	0.0089	-0.0255
-70.00	-0.334	1.2155	0.2673	-0.50	0.086	0.0089	-0.0264
-65.00	-0.406	1.1252	0.2465	0.00	0.142	0.0089	-0.0273
-60.00	-0.470	1.0213	0.2241	0.50	0.198	0.0089	-0.0281
-55.00	-0.524	0.9070	0.2009	1.00	0.251	0.0089	-0.0284
-50.00	-0.568	0.7857	0.1781	1.50	0.300	0.0090	-0.0281
-45.00	-0.601	0.6610	0.1565	2.00	0.346	0.0091	-0.0272
-40.00	-0.627	0.5366	0.1346	2.50	0.390	0.0091	-0.0260
-35.00	-0.650	0.4163	0.1123	3.00	0.433	0.0093	-0.0247
-30.00	-0.663	0.3033	0.0967	3.50	0.474	0.0096	-0.0235
-25.00	-0.670	0.2008	0.0894	4.00	0.518	0.0100	-0.0227
-21.00	-0.708	0.1295	0.0703	4.50	0.564	0.0104	-0.0225
-20.00	-0.727	0.1135	0.0613	5.00	0.611	0.0107	-0.0224
-19.00	-0.750	0.0984	0.0501	5.50	0.655	0.0112	-0.0219
-18.00	-0.775	0.0841	0.0374	6.00	0.696	0.0118	-0.0212
-17.00	-0.801	0.0709	0.0238	6.50	0.735	0.0124	-0.0204
-16.00	-0.823	0.0588	0.0099	7.00	0.776	0.0131	-0.0198
-15.00	-0.840	0.0479	-0.0035	7.50	0.819	0.0137	-0.0195
-14.00	-0.848	0.0383	-0.0157	8.00	0.860	0.0144	-0.0190

B.4. AERODYNAMIC AIRFOIL COEFFICIENTS FOR THE THREE WTS

α [°]	C_L [-]	C_D [-]	C_M [-]		α [°]	C_L [-]	C_D [-]	C_M [-]
8.50	0.896	0.0153	-0.0181		60.00	0.671	1.0213	-0.2789
9.00	0.930	0.0163	-0.0169		65.00	0.580	1.1252	-0.2985
9.50	0.963	0.0174	-0.0159		70.00	0.477	1.2155	-0.3169
10.00	0.996	0.0186	-0.0149		75.00	0.367	1.2893	-0.3339
10.50	1.027	0.0199	-0.0139		80.00	0.246	1.3458	-0.3496
11.00	1.057	0.0213	-0.0129		85.00	0.118	1.3833	-0.3636
11.50	1.086	0.0228	-0.0120		90.00	0.000	1.3971	-0.3744
12.00	1.112	0.0246	-0.0108		95.00	-0.092	1.3833	-0.3801
12.50	1.131	0.0267	-0.0092		100.00	-0.172	1.3458	-0.3813
13.00	1.145	0.0293	-0.0074		105.00	-0.254	1.2893	-0.3786
13.50	1.155	0.0322	-0.0057		110.00	-0.334	1.2155	-0.3725
14.00	1.162	0.0353	-0.0038		115.00	-0.407	1.1252	-0.3633
14.50	1.169	0.0385	-0.0017		120.00	-0.470	1.0213	-0.3519
15.00	1.172	0.0423	-0.0007		125.00	-0.523	0.9070	-0.3392
15.50	1.171	0.0468	-0.0021		130.00	-0.568	0.7857	-0.3258
16.00	1.165	0.0522	-0.0057		135.00	-0.603	0.6609	-0.3128
16.50	1.155	0.0582	-0.0114		140.00	-0.627	0.5366	-0.3030
17.00	1.142	0.0649	-0.0187		145.00	-0.641	0.4165	-0.2988
17.50	1.127	0.0722	-0.0272		150.00	-0.663	0.3033	-0.2980
18.00	1.110	0.0798	-0.0366		155.00	-0.706	0.2002	-0.3044
18.50	1.092	0.0879	-0.0466		160.00	-0.727	0.1135	-0.3498
19.00	1.073	0.0963	-0.0567		165.00	-0.679	0.0494	-0.4461
19.50	1.055	0.1048	-0.0667		170.00	-0.547	0.0100	-0.5000
20.00	1.038	0.1135	-0.0761		175.00	-0.323	-0.0035	-0.3913
20.50	1.023	0.1223	-0.0846		180.00	0.000	0.0100	0.0000
21.00	1.010	0.1311	-0.0923					
21.50	0.998	0.1399	-0.0992					
22.00	0.988	0.1488	-0.1054					
22.50	0.980	0.1578	-0.1108					
23.00	0.972	0.1668	-0.1157					
23.50	0.966	0.1759	-0.1199					
24.00	0.961	0.1851	-0.1236					
24.50	0.957	0.1944	-0.1268					
25.00	0.954	0.2037	-0.1296					
25.50	0.952	0.2132	-0.1320					
26.00	0.950	0.2227	-0.1341					
26.50	0.949	0.2324	-0.1359					
27.00	0.948	0.2422	-0.1375					
27.50	0.948	0.2520	-0.1390					
28.00	0.948	0.2620	-0.1403					
30.00	0.947	0.3033	-0.1457					
35.00	0.930	0.4155	-0.1671					
40.00	0.896	0.5366	-0.1936					
45.00	0.858	0.6612	-0.2167					
50.00	0.811	0.7857	-0.2374					
55.00	0.749	0.9069	-0.2582					

Appendix C

VKI High-Performance Computing (HPC): Infrastructure & resources

C.1 Hardware

All computational analysis presented throughout this thesis were performed on the von Karman Institute's High-Performance Computing cluster (VKI-HPC), equipped with cutting-edge hardware, which consist of:

- A file server with 70 TB storage in Redundant Array of Independent Disks (RAID) 60.
- A Single Rail InfiniBand (4xEDR (Enhanced Data Rate) 100 GBPS, InfiniBand) for:
 1. Network File System (NFS) traffic,
 2. Message Passing Interface (MPI) traffic,
- 6 Nodes with Dual AMD Naples EPYC 7551 (32 cores/64 threads each) and 1 TB of RAM in 32 DIMM for 2133 MHz with 8 memory channels.
- 14 Nodes with Dual AMD Rome EPYC 7742 (64 cores/128 threads each) and 1 TB of RAM in 32 DIMM for 3200 MHz with 8 memory channels.
- 2 Nodes with Dual AMD Milan EPYC 7xxx series (64 cores/128 threads each) and 1 TB of RAM in 32 DIMM for 3200 MHz with 8 memory channels.

The VKI-HPC cluster is operating on Fedora release 30.

C.2 Software

The modified open-source versions of the Weather Research and Forecasting (**WRF**) **v4.3**, **v4.3.3**, and **v4.4.1** and **WRF** Pre-processing System (**WPS**) **v4.3.1** and **v4.4** models were used to perform high-fidelity multi-scale atmospheric boundary layer coupled wind turbine simulations in **WRF-LES** framework (**WLGD** and **WLGL**). All modifications to **WRF** and **WPS** models were done in **Fortran 77** and **Fortran 90**.

Two-dimensional Reynolds-Averaged Navier-Stokes (**RANS**) simulations were performed on a commercial **STAR-CCM+ v13.04.011** parallel server and these results were inputted into the VKI's in-house open-source Broadband and Tonal Models for Airfoil Noise (**BATMAN**) code written in **Python 3.8** to perform aeroacoustic noise computations.

A free and open-source Geographic Information System (**GIS**), named **QGIS 3.32.1-Lima**, was used to view, edit, and analyze the high-resolution Coordination of information on the environment (**CORINE**) Land Cover (**CLC**) and the Shuttle Radar Topography Mission (**SRTM**) geospatial data used in **WPS v4.1**.

Numerical results were analyzed and visualized through **Python 3.7** scripting and **ParaView v5.6.0**, which is an open-source multiple-platform application for interactive, scientific visualization. The commercial multi-paradigm programming language and numeric computing environment **MATLAB v2022a update 5** was previously used for **WRF** data processing. The **WRF** model outputs in network Common Data Form (**netCDF**) 4 format were further post-processed using the **netCDF Operators (NCO)** utilities.

This **L^AT_EX** document has been generated in **T_EXstudio v4.6.2**. Schematics and sketches were further edited with the open-source vector graphics editor **Inkscape v1.3**.

C.3 Computational overhead

Table C.1 provides information on the computational resources used and the physical (wall-clock) time spent on all simulations analyzed in Chapters 6 to 8.

Table C.1: Details of the computational resources used and the physical (wall-clock) time spent on all simulations analyzed in Chapters 6 to 8.

Simulation	Identifier	Simulation type	Model version	Chapter/section	Node name	# of nodes	# of cores	# of runs	Allocated memory	Wall-clock time
WRF-LES	noCPMxRy, CPMxRy	WRF v4.4.1	Chapter 6	LES	Rome	2	121	12	800 GB	~36 hours
WRF-LES	WLGD,WLGL	WRF v4.4.1	Section 7.1	LES	Rome	2	126	2	800 GB	~10 hours
WRF-LES	WLGL	WRF v4.4.1	Section 7.1.3	LES	Naples	1	64	15	800 GB	~6 hours
WRF-LES	WLGD	WRF v4.4.1	Section 7.2	LES	Rome	2	126	1	800 GB	~22 hours
WRF-LES	WLGD,WLGL	WRF v4.3, WRF v4.4.1	Section 7.3	LES	Rome	2	64	6	800 GB	~24 hours
WRF-LES	WLGL	WRF v4.4.1, WPS 4.4	Section 8.1	URANS-LES	Rome	4	126	3	800 GB	~216 hours
WRF	-	WRF v4.3.3, WPS v4.3.1	Section 8.2.3	URANS	Rome	2	126	1	800 GB	~24 hours
WRF-LES	WLGL	WRF v4.4.1, WPS 4.4	Section 8.2.4	URANS-LES	Rome	2	64	1	800 GB	~168 hours
STAR-CCM+	Airfoil	v13.04.011	Section 8.2.5	RANS	-	-	32	9	1.5 GB	~0.5 hour
STAR-CCM+	Wind turbine	v13.04.011	Section 8.2.5	RANS	-	-	64	71	1.5 GB	~60 hours

Note. RANS simulations were run on a high-end workstation, utilizing dual AMD EPYC 7742 64-Core Processor and 1 TB of RAM in 32 DIMM for 3200 MHz with 8 memory channels. Number of runs presented herein correspond to successful computations only. Wall-clock time is reported for each case.

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