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CHARACTERIZATION OF THE PRESSURE FLUCTUATIONS WITHIN AN AIRFOIL BOUNDARY LAYER USING WMLES

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Abstract. Large-eddy simulation (`LES`) of an airfoil trailing edge noise has largely been restricted to low Reynolds numbers due to prohibitive computational cost. Wall modelled LES (`WMLES`) offers a computationally cheaper alternative that makes Reynolds numbers of practical importance accessible. We examine the capability of `WMLES` approach to predict the broadband noise generated by a controlled-diffusion blade. All simulations are carried out for a Mach number of 0.5, a chord-based Reynolds number of 2.29×10^6, and at angle of attack 4°. Detailed comparisons are made with experimental data.

1. Introduction

It is widely accepted that trailing edge noise is the dominant noise source for modern wind turbines [6]. The present work is carried out within the `SCONE` (Simulation of Contra Rotating Open Rotor and fan broadband NoisE with reduced order modelling) project that is part of the FP7 Clean Sky Joint Undertaking of the European Union. Such a project aims at investigating the noise associated with `CROR`/`UHBR` fan technologies in order to reach optimal noise reduction [2]. Despite the availability of comprehensive trailing edge noise measurement databases, several fundamental questions remain unanswered [4]. For example, existing scaling laws for trailing edge noise were found lacking in recent studies. Since it is experimentally challenging to measure pressure on the surface without affecting the flow field [8], a computational approach is usually chosen. A detailed characterization of the surface pressure fluctuations provides an accurate input for current analytical approaches, thus improving the far field predictions. The first objective of the `SCONE` project is to address the flow over a controlled-diffusion (`CD`) airfoil. The foil geometry was originally part of an air conditioning unit developed by Valeo and later on was slightly re-designed to imprint on it a load similar to that of a `CROR` blade [6]. Herein, the configuration is a replica of the experiments performed within the `CRORTET` Clean Sky project. Due to prohibitive computational cost, high-fidelity numerical simulations of trailing edge noise have largely been restricted to low Reynolds numbers. The present work is a step towards developing the capability to predict trailing edge noise from first principles at Reynolds numbers of practical importance.

2. Mathematical modelling

The compressible Navier–Stokes equations are solved numerically using the `CharLES`$^{\mathrm{X}}$ solver [1], a control-volume-based, finite-volume solver on unstructured grids. The numerical method is formally second-order accurate in space, although it achieves fourth-order accuracy on a uniform mesh containing only hexahedral cells. Time integration is performed using a third-order low-storage Rung–Kutta–Wray (`RKW3`) scheme [9]. The code is parallelised using the message passing interface (`MPI`) protocol and is highly scalable on a large number of processors. The solver relies on the Vreman subgrid-scale model [7] to represent effect of unresolved small-scale fluid motions. In the framework of wall-modelled `LES`, `LES` is performed on a computational grid designed to resolve the large-scale eddies in the outer region of the boundary layer. The turbulence dynamics in the near-wall region is modelled, and its effect is provided to the `LES` as an approximate boundary condition. Given an instantaneous velocity $\mathcal{U}_i$ at height $x_2 = h_{\mathrm{wm}}$ measured perpendicularly to the wall, the instantaneous wall shear stress vector $\tau_{w,i}$ is estimated by solving a mono-dimensional ordinary differential equation (`ODE`). In the present study, we use the equilibrium stress-balanced model of the form [5]:

$$\frac{d}{dx_2}\left[(\mu+\mu_{t,\mathrm{wm}})\frac{d\mathcal{U}}{dx_2}\right]=0\,,\;\; \frac{d}{dx_2}\left[c_{\mathcal{P}}\left(\frac{\mu}{\mathrm{Pr}}+\frac{\mu_{t,\mathrm{wm}}}{\mathrm{Pr}_{t,\mathrm{wm}}}\right)\frac{d\mathcal{T}}{dx_2}\right]=-\frac{d}{dx_2}\left[(\mu+\mu_{t,\mathrm{wm}})\mathcal{U}\frac{d\mathcal{U}}{dx_2}\right]\,,$$

and the wall-model eddy-viscosity is taken as $\mu_{t,\mathrm{wm}} = \kappa\rho\sqrt{\frac{\tau_w}{\rho}}\,y\left[1-\exp\left(-x_2^+/A^+\right)\right]^2$.

3. Computational grid and flow parameters

The computational grid around the controlled-diffusion airfoil is topologically a C-type, and the domain extends to $20c$ (20 chord length) and $20c$ in the streamwise (x_1) and wall-normal (x_2) directions. Although there is no available experimental data dealing with the spanwise correlation length, the reference wall-resolved `LES` [3] suggests that a spanwise extent L_{x_3} of $2\delta_{\max}$ leads to a reasonable agreement with experimental data for the correlation length ℓ_z. Characteristic boundary conditions are enforced in the far-field. Periodic boundary conditions are imposed in the spanwise direction. Details of the simulated flows are summarized in Table 1, where Ma_∞, Re_c, AoA, L_{x_3}, N_{cells}, Δ_t indicate the Mach and Reynolds numbers, the angle of attack, the width of the blade in the spanwise direction, the number of cells, and the time step, respectively.

4. Numerical results

In Figure 1, the three-dimensional features of vortex structures and its breakdown processes in the laminar–turbulent transition region near the leading edge are visualized by the instantaneous iso-surfaces of the second invariant of velocity gradient tensor Q defined as $Q = (\omega^2 + 2\mathcal{S}_{ij}\mathcal{S}_{ij})/4$. The Q iso-surfaces are coloured by streamwise velocity to

case	Ma_∞	Re_c	AoA	L_{x_3}	N_{cells}	Δt	LES
$\mathcal{C}_1$	0.5	2.29×10^6	$4°$	$10\%\ c$	225.5M	2.58×10^{-5}	WRLES
$\mathcal{C}_2$	0.5	2.29×10^6	$4°$	$10\%\ c$	19.9M	1.02×10^{-5}	WMLES
$\mathcal{C}_3$	0.5	2.29×10^6	$4°$	$10\%\ c$	19.9M	1.02×10^{-5}	WRLES

Table 1: Main parameters used in the present computations.

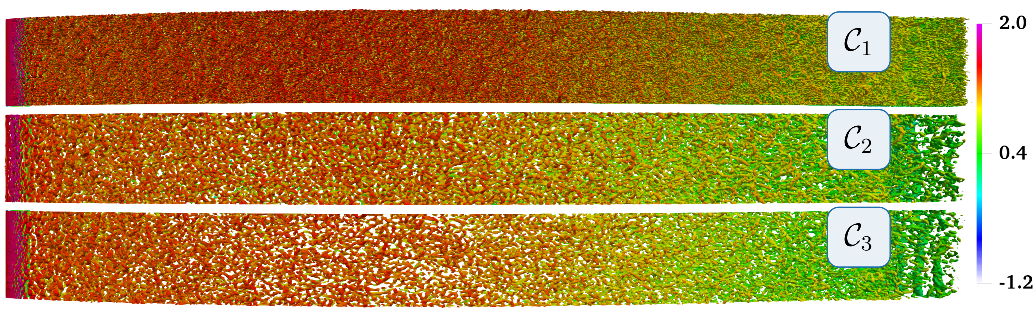


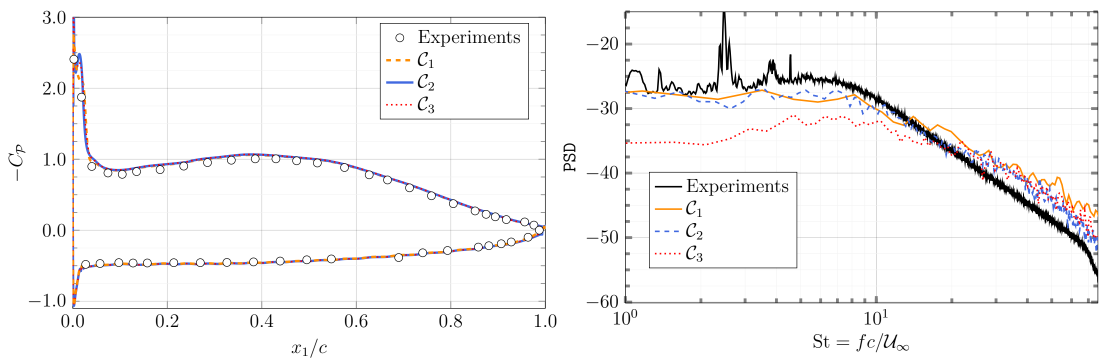
Figure 1: Q-criterion ($Qc^2/\mathcal{U}_\infty^2 \sim 950$) coloured by the normalized longitudinal instantaneous velocity $\mathcal{U}_1/\mathcal{U}_\infty$ of the $\mathcal{C}_1$ case.

approximately identify the height of these vortex structures. It is found that the nature of the developed turbulent structures is largely influenced by the size and the structure of the recirculation bubble. Furthermore, the LES with wall model with equilibrium assumptions (case $\mathcal{C}_2$) does not show a laminar separation, and the flow becomes turbulence without the clear 2D vortex breakdown as it shown in $\mathcal{C}_1$ and $\mathcal{C}_3$. In fact, case $\mathcal{C}_2$ shows a weaker resistance against separation, and therefore, separation occurs earlier.

Figure 2a presents the pressure coefficient for the three cases. The overall comparison is very close to the the experimental results for the $\mathcal{C}_2$ simulation. We recover the feature described earlier, with mismatching locations in the separation zone. However it is very interesting to see that the impact for the downstream region is very limited as almost no difference is visible in the leading edge region. Therefore, it seems reasonable to conclude that the method is particularly well adapted for these type of flow problems, at least for the estimation of the leading edge turbulent boundary layer characteristics. The resulting spectrum of the fluctuating pressure is plotted in Figure 2b and again the results are very close to the reference with moderate deviations. This is possible because near the trailing edge at $x_1/c = 0.98$, the WMLES case is fine enough to resolve the large-scale motions. Thus, the PSD profiles in the low-frequency range tend towards the the reference case.

5. Conclusion

Wall modeled large-eddy simulations WMLES are used to investigate a controlled-diffusion blade trailing edge noise at full–scale Reynolds numbers. Detailed comparisons are made with experimental data. The computational cost of WMLES approach is reduced by two orders of magnitude compared to that of classic WRLES by (a) reducing the number of grid points by roughly $\sim 1/20$ (b) increasing the time step by more than one order of mag-



(a) (b)

Figure 2: (left) Airfoil pressure distribution; (right) wall pressure spectrum at $x_1/c = 0.98$.

nitude because the grid for the `WRLES` is much less constrained by the acoustic time-step limitation. Therefore, `WMLES` approach is very interesting from a modelling perspective as a large number of configuration can be quickly studied. It also allows to perform 3D blades simulations at moderate cost.

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References

[1] I. Bermejo-Moreno, L. Campo, J. Larsson, J. Bodart, D. Helmer, and J. K. Eaton. Confinement effects in shock wave/turbulent boundary layer interactions through wall-modelled large-eddy simulations. *Journal of Fluid Mechanics*, 758:5–62, 2014.

[2] R. Boukharfane, J. Bodart, M. C. Jacob, L. Joly, T. Bridel-Bertomeu, and T. Node-Langlois. Characterization of the pressure fluctuations within a controlled-diffusion airfoil boundary layer at large Reynolds numbers. In *25th AIAA/CEAS Aeroacoustics Conference*, page 2722, 2019.

[3] A. Grebert, J. Bodart, and L. Joly. Investigation of wall-pressure fluctuations characteristics on a NACA0012 airfoil with blunt trailing edge. In *22nd AIAA/CEAS Aeroacoustics Conference*, page 2811, 2016.

[4] M. Herr and M. Kamruzzaman. Benchmarking of trailing-edge noise computations—outcome of the BANC-II workshop. In *19th AIAA/CEAS Aeroacoustics Conference*, page 2123, 2013.

[5] J. Larsson, S. Kawai, J. Bodart, and I. Bermejo-Moreno. Large eddy simulation with modeled wall-stress: recent progress and future directions. *Mechanical Engineering Reviews*, 3(1):15–00418, 2016.

[6] S. Moreau and M. Roger. Effect of airfoil aerodynamic loading on trailing edge noise sources. *AIAA journal*, 43(1): 41–52, 2005.

[7] A. W. Vreman. An eddy-viscosity subgrid-scale model for turbulent shear flow: algebraic theory and applications. *Physics of Fluids*, 16(10):3670–3681, 2004.

[8] W. R. Wolf and S. K. Lele. Trailing-edge noise predictions using compressible large-eddy simulation and acoustic analogy. *AIAA journal*, 50(11):2423–2434, 2012.

[9] A. A. Wray. Minimal storage time advancement schemes for spectral methods. *NASA Ames Research Center, California, Report No. MS*, 202, 1990.