Large Eddy Simulation of Sound Sources on a Cambered Airfoil

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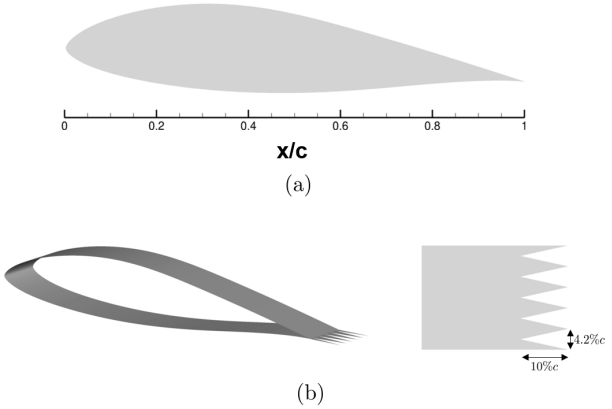
Introduction

With the advancements in Ultra High Bypass Ratio (UHBR) technology resulting in quieter engines, airframe noise reduction becomes imperative to achieving the overall aircraft noise reduction. One of the major contributors to the airframe noise is the Trailing Edge Noise (TEN) which can be broadband and tonal in nature. Among the various causes of TEN illustrated in Brooks, Pope and Marcolini (BPM)[1], the broadband noise generated by the scattering of the Turbulent Boundary Layer (TBL) at the trailing edge resulting in TBL-TEN is particularly of interest and is present in various airframe components such as slats and flaps.

With an increased emphasis on using scale resolving simulations for the prediction of airframe noise, it is still outside the realm of existing computational capabilities to use Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) on a full aircraft wing at an operational Reynolds number (Re). Note that the computational points required to perform a DNS varies as $N_{xyz} \propto Re_{l_0}^3$ and $N_{xyz} \propto Re_{l_0}^{13/7}$ for LES, where l_0 is the integral length scale of turbulence. With these scaling, the DNS of a full aicraft wing is not possible until 2080 (see Spalart [2]) and LES until 2030 (see Piomelli [3]).

Wall-Modeled LES (WMLES) where the computationally demanding inner layer dynamics of the TBL are modeled and the energetic outlayer (80%-90%) of the TBL are resolved in an LES fashion, provides a favorable scaling with $N_{xyz} \propto Re_{l_0}$. This method is applied in the current work using the commercial solver Multi-Grid Large Eddy Turbulence (MGLET). Note that, the application of computationally less demanding WMLES to the prediction of airframe noise is not trivial and is an ongoing discussion. Contrary opinions can be found in literature regarding the applicability of WMLES for predicting TEN. For e.g., Larsson et al. [4] emphasized the importance of the inner-layer turbulence for the accurate prediction of the TEN. They opined that by modeling the inner layer turbulence, one can only predict the sound only upto the outer layer frequencies, given by (u_τ/δ) and hence advocated against the use of WMLES. For the case considered in the current work, this outer layer frequency limit corresponds to a frequency as low as 250 Hz-450 Hz. On the other hand, George and Lele [5] have successfully demonstrated the use of WMLES for predicting the TEN across a wide range of frequencies, not restricted by the limit (u_τ/δ). To add to this ongoing discussion, the current work aims to i) apply and validate WMLES in the framework of MGLET to predict the TEN of a well known cambered wind turbine profile DU96-180 [see Fig. 1(a)] described in the 'Benchmark Problems for Airframe Noise Computations (BANC-II) [6]' and ii) reduce the TBL-TEN using retrofitted serrations [see Fig. 1(b)].



(a)

(b)

Figure 1: (a) The cambered wind turbine profile DU96-180. (b) The profile is retrofitted with serrations to induce a noise reduction.

Simulation Method

Wall-Modeled LES in the current work is applied in the framework of Multi-Grid Large Eddy Turbulence (MGLET) solver (see Manhart and Friedrich [7]). MGLET is a finite volume, cutcell-Immersed Boundary Method solver. Filtered incompressible Navier-Stokes equations (Eqn. [1]-[2]) are solved using the second order accurate spatial discretization and third order accurate temporal discretization schemes. A Werner-Wengle [8] type of wall stress model is used to model the inner layer turbulence. The τ_{ij} in Eqn. [2] contains the subgrid scale contributions given by a Smagorinsky model with the model constant $C_s = 0.1$. Note that, a novel hydrodynamic-acoustic splitting method that enables the acoustic feedback onto the flow is also available in MGLET, however not used in the current work (see Ewert and Kreuzinger [9]).

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} = -\frac{\partial u_i u_j}{\partial x_j} - \frac{1}{\rho_0}\frac{\partial p^{ic}}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

The acoustics is obtained by subsequently solving the Acoustic Perturbation Equations (APE 1) (see Ewert and Schröder [10]), which uses the source term $\frac{1}{\rho_0}\frac{\partial p^{ic}}{\partial x_i}$ computed by the WMLES. In MGLET, wave form of the APE-1 is solved (see Eqn. [3]), wherein the the source terms from WMLES are fly-by coupled to Eqn. [3] to compute the total pressure perturbations p'. The acoustic pressure perturbations can be further obtained by removing the incompressible part from these perturbations, i.e., $p^a = p'$ - p^{ic}.

$$\frac{\partial^2 p'}{\partial t^2} - c^2\frac{\partial^2 p'}{\partial x_i^2} = -c^2\frac{\partial^2 p^{ic}}{\partial x_i^2} \quad (3)$$

The flow parameters specified in the workshop of 'Benchmark Problems for Airframe Noise Computations (BANC-II) [6]' will be used for the current study with a free-stream velocity, u_∞ = 60 m/s, angle-of-attack, $\alpha = 4°$, and a chord based Reynolds number, $\mathrm{Re}_c = 1.2 \times 10^6$.

For the WMLES, the finest level of grid resolution maintained corresponds to Δ_{min} = 0.00025m, i.e., Δy^+ = 50 in wall units and $\Delta/\delta = 0.033$ in outer layer units. This resolution is well within the recommended WMLES resolution by Larsson et al. [4], i.e., (Δ_x/δ, Δ_y/δ, Δ_z/δ) = (0.08, 0.02 - 0.05, 0.05). This results in a computational grid with 43 $\times$ 10^6 points. Each simulation is carried out with 1000 CPUs on the German Aerospace Center's CARA cluster. The total computational effort spent on each simulation (WMLES + APE) corresponds to a modest 9.5kCPUh for a signal length sampled upto 0.1s.

With a resolution of $\Delta y^+ = 50$ near the wall, additional treatment is needed to ensure the correct onset of turbulence leading to right amount of turbulence near the trailing edge of the profile. In the current work, this is done by adding roughness to the wall model according to the Eqn. [4](see Schlichting [11])

$$\tau_w = \frac{\rho u_p^2}{\left(\frac{\ln(dx/k_s)}{\kappa} + c\right)^2} \quad (4)$$

where $\kappa = 0.4$ and $c = 8.5$ are model constants, k_s is the roughness height, u_p is the interpolated wall parallel velocity at a distance dx from the wall. The open parameter k_s and the position where this roughness needs to be applied on the profile to accurately obtain the turbulence needs is calibrated using the skin friction (C_f) coefficient comparison with XFOIL/RANS and is discussed in the following section.

Results

Effect of roughness

The roughness according to Eqn. [4] is applied at various positions on the profile (see Fig. 2). The resulting C_f distribution is compared with the XFOIL/RANS data as shown (see Fig. 3). The comparison shows that an accurat C_f distribution is obtained towards the trailing edge when roughness is applied between $x = 0.2c$ - $0.4c$ (middle section). Furthermore, the importance of applying this roughness is qualitatively illustrated in Fig. 4. Without the roughness, a considerably thicker TBL is obtained. Due to the absence of finer scales, the TBL lacks the momentum and hence an early detachment as seen in Fig. 4 is inevitable. The effect of various

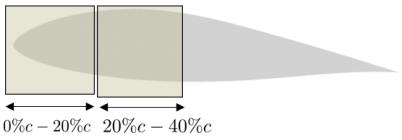


Figure 2: Illustration of the positions along the profile where roughness is applied according to Eqn. [4] to aide the onset of turbulence

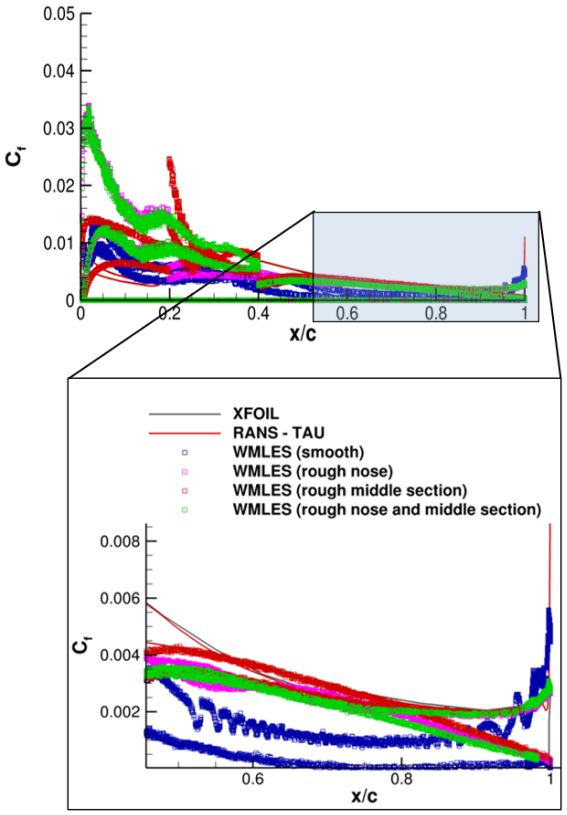


Figure 3: Comparison of C_f distribution obtained from WMLES with XFOIL and RANS data for various roughness scenarios.

afore-mentioned roughness scenarios on the Power Spectral Density of the surface pressure fluctuations (PSD) at $x/c = 0.99$ on the suction side and is shown in Fig. 5. The absence of roughness results in a over-prediction in the low frequencies. This can be attributed to the formation of larger eddies in the thicker and separated TBL seen in Fig. 4. With roughness applied, the prediction improves and a good agreement is seen with the measurements car-

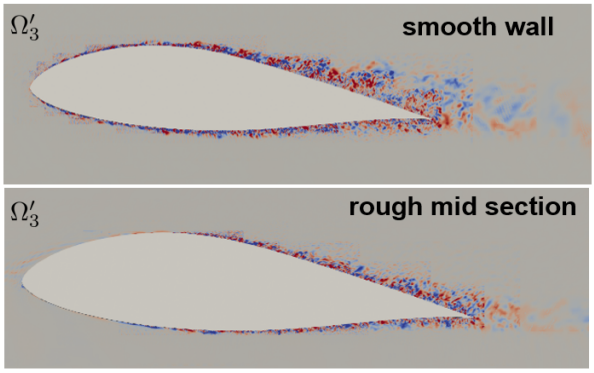


Figure 4: 2D contours of vorticity fluctuations for smooth and rough airfoil surfaces, showing the effect of roughness on the TBL.

ried out at Acoustic WinTunnel Braunschweig (AWB). However, unlike the C_f and PSD spectrum, the position where roughness is applied has no major effect on the far-field SPL spectrum (see Fig. 6).

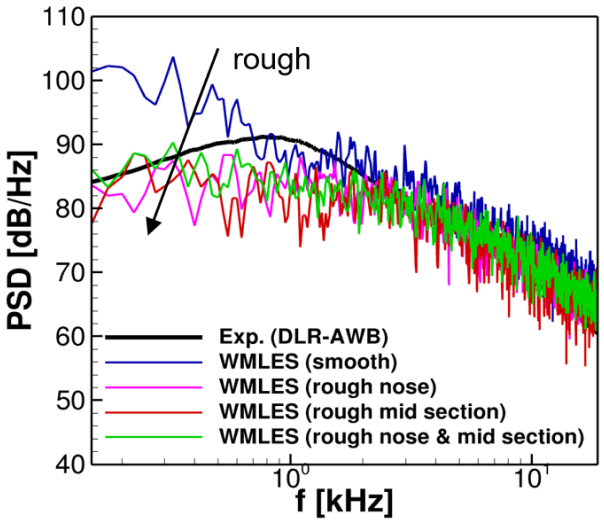


Figure 5: The Power Spectral Density of the surface pressure fluctuations (PSD) at $x/c = 0.99$ on the suction side of the profile. The experimental data is from the measurements carried out at Acoustic WinTunnel Braunschweig (AWB).

TEN Reduction by Serrations

WMLES is further applied to predict the well established noise reduction feature of serrations. The profile is retrofitted with serrations extending by 10%c [see Fig. 1(b)]. The roughness is applied at a $x = 0.2c$-$0.4c$ on the profile. The far-field narrow band spectrum at an observer position $r = 1$m shows a clear reduction in SPL in the low-mid frequency ranges and an additional penalty noise in the high frequency ranges (see Fig. 7). This is attributed to the role of the serrations in breaking up the larger eddies going into the wake in to finer scales. This effect of serrations is widely reported in literature, for e.g., Jones and Sandberg [12] and the WMLES in the current work reproduces this effect.

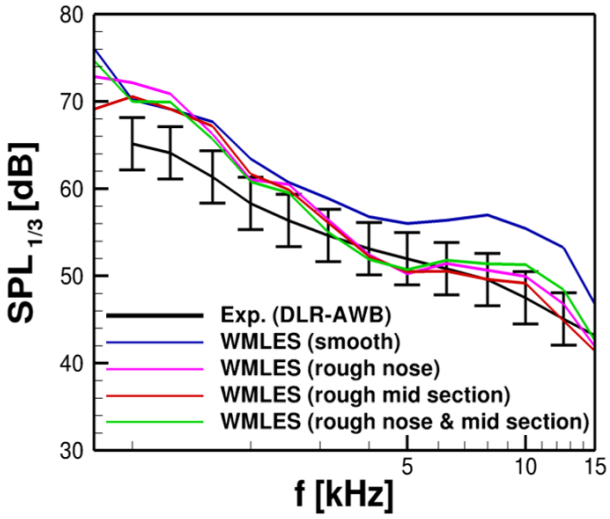


Figure 6: Effect of roughness on the far-field $(1/3)^{rd}$ octave band Sound Pressure Level (SPL) spectrum. The experimental data is from the measurements carried out at Acoustic WinTunnel Braunschweig (AWB), and is availbale for benchmarking in BANC-II [6].

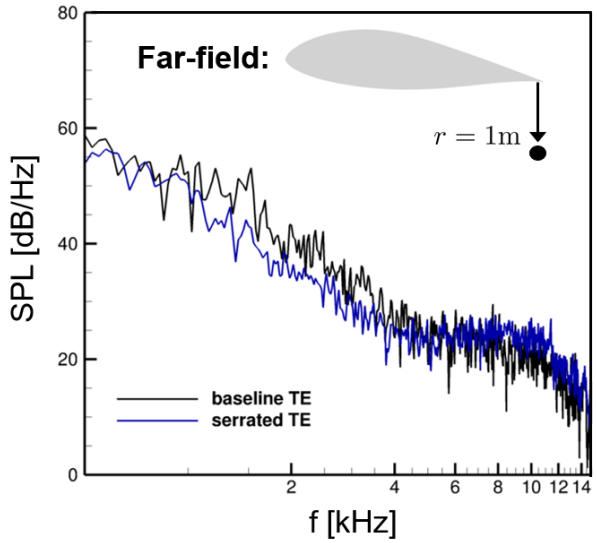


Figure 7: The far-field narrow-band Sound Pressure Level (SPL) measured at an observer distance r=1m for the baseline and serrated DU96-180 profiles.

Conclusion

In the framework of MGLET, Wall-Modeled LES is applied and validated on a cambered airfoil, i.e., DU96-180. The onset of turbulence for the WMLES is facilitated by applying roughness on the profile. The significance of this roughness on the near-wall flow and far-field acoustics are discussed. In contrary to the observations made in Larsson et al. [4], the SPL prediction is not only limited upto f=u_τ/δ rather across a wide range of frequencies. The sound pressure level spectrum shows a good agreement to the experimental data reported in BANC-II. Furthermore, the prediction capabilities of the WMLES is further verified on a noise reduction by retro-fitted serrations. The method reproduces the wisely reported

effect of serrations, i.e., a reduction in low-mid frequency ranges and an additional noise in higher frequencies.

The study strongly advocates for the use of WMLES as a highly effective scale resolving simulation method, capable of producing the relevant near-wall and far-field physics, required for accurate sound prediction from airframe components.

References

[1] Brooks, T. F., Pope, D. S., Marcolini, M. A.: Airfoil self-noise and prediction. Washington, DC: National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Division, Vol. 1218 (1989).

[2] Spalart, P. R.: Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach. In Proceedings of first AFOSR international conference on DNS/LES. Greyden Press (1997).

[3] Piomelli, U.: Large eddy simulations in 2030 and beyond. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, Vol. 372, 20130320, (2014).

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

[5] George, K. J., Lele, S. K.: Large eddy simulation of airfoil self-noise at high Reynolds number. In 22nd AIAA/CEAS Aeroacoustic Conference, Vol. 30 (2016).

[6] Herr, M., Kamruzzaman, M.: Benchmarking of Trailing-Edge Noise Computations—Outcome of the BANC-II Workshop. In 19th AIAA/CEAS Aeroacoustics Conference, 2123 (2013).

[7] Manhart, M., Friedrich, R.: DNS of a turbulent boundary layer with separation. International Journal of Heat and Fluid Flow, Vol. 23(5), 572-581 (2002).

[8] Werner, H., Wengle, H.: Large-eddy simulation of turbulent flow over and around a cube in a plate channel. In Turbulent shear flows. Springer, Berlin, Heidelberg, Edn. 8, (1993).

[9] Ewert, R., Kreuzinger, J.: Hydrodynamic/acoustic splitting approach with flow-acoustic feedback for universal subsonic noise computation. Journal of Computational Physics, Vol. 444, 110548 (2021).

[10] Ewert, R., Schr der, W.: Acoustic perturbation equations based on flow decomposition via source filtering. Journal of Computational Physics, Vol. 188(2), 365-398 (2003).

[11] Schlichting, H., Gersten, K.: Boundary-layer theory. Springer (2016).

[12] Jones, L. E., Sandberg, R. D.: Acoustic and hydrodynamic analysis of the flow around an aerofoil with trailing-edge serrations. Journal of Fluid Mechanics, Vol. 706, 295-322 (2012).