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Numerical Analysis of Parameters Affecting Turbulent Boundary Layer Trailing-Edge Noise

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ABSTRACT: In the present study, one of the most important mechanisms of aerodynamic noise generation is investigated numerically. The Large-eddy simulation approach used to solve the unsteady flow equations of the turbulent boundary layer with Mach number 0.06 over a flat plate of length 30 cm. Lund's inflow boundary model used to reduce computational cost. In order to evaluate the parameters affecting trailing edge noise (including surface pressure spectra, the spanwise length scale of the surface pressure fluctuations and eddy convection velocity), data of surface pressure fluctuations values in different points over the flat plate surface are collected using the probe tool in OpenFOAM software. Based on the calculated parameters affecting the trailing edge noise, the far-field noise is predicted using the analytical Amiet-Roger model. The results showed that the numerical solution method used in this study is capable of predicting the effective parameters on the trailing edge noise with a reasonable computational cost. Studying the spectral parameters affecting the turbulent boundary layer trailing edge noise showed that prediction and direct estimation of these parameters can be used to predict the far-field noise propagation. Moreover, these parameters can provide proper information on the physics of the flow and dimensions and lifetime of turbulent boundary layer vortex structures.

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1. INTRODUCTION

Airfoil self-noise is one of the most important sources of aerodynamic noise during aircraft landing. The produced noise is due to the interaction of fluid flow with the airfoil surface and is important not only in aircraft but in equipment such as wind turbines and fans. The mechanisms associated with the airfoil self-noise classified in Ref. [1], based on the frequency range to tonal and broadband noises, namely as laminar and turbulent boundary-layer noise and bluntness noise. Turbulent Boundary Layer Trailing Edge (TBL-TE) broadband noise is one of the most important airfoil self-noise mechanisms. Due to the wide frequency range of the broadband noise, understanding and modeling of the physics associated with its generation and propagation are important for the design of more silent devices.

Amiet [2] and Howe [3] postulated that the far-field airfoil Trailing Edge (TE) noise is due to the convection of incident pressure fluctuations on the surface over the trailing edge which eventually scattered in the form of acoustic waves. In the most aeroacoustic analysis, two basic approaches used for prediction of far-field trailing edge noise; formulations based on the Lighthill [4] acoustic analogy that need hydrodynamic velocity field around the TE, or linearized hydroacoustic methods that use the induced hydrodynamic pressure field at some distance upstream of the TE. The majority of noise prediction methods for trailing edge, such as Amiet [2] and Howe [3], formulated based on surface pressure fluctuations. According to Amiet [2] and Howe [3] models, the frequency-dependent power spectral density, the spanwise length scale of the Surface Pressure Fluctuations (SPFs) and the convection velocity in the TE region are most important parameters in predicting the far-field trailing edge noise. In the most aeroacoustic analysis, the Chase [5] and Goody [6] models are used for estimation of the power spectral density and the Corcos [7] model for the spanwise coherence length and the convection velocity instead of calculating these parameters numerically. Direct numerical prediction of the frequency-dependent of these parameters forms the basis of the current study.

The present study is aimed to evaluate the applicability of the Navier-Stokes-based computational tool with the boundary-layer recycling model of Lund [8] to simulate incompressible flow over a flat plate and to determine the frequency-dependent parameters affecting the far-field noise prediction under a fully developed turbulent boundary-layer of low-Mach-number flow. The Large-Eddy Simulation (LES) approach by employing dynamic Smagorinsky sub-grid-scale model in the open-source package OpenFOAM 2.4.0 used to obtain numerical data. The spanwise length scale and the convection velocity of the turbulent eddies are calculated by obtaining the unsteady surface pressure in both spanwise and streamwise directions. The methodology is described in section 2 and the main outcomes of the present investigation are presented in section 3.

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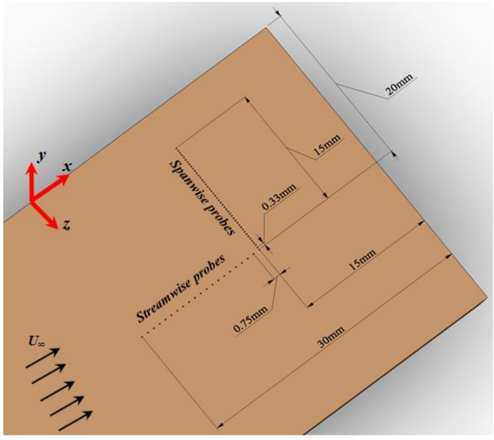

Fig. 1. Probes array over the flat plate surface

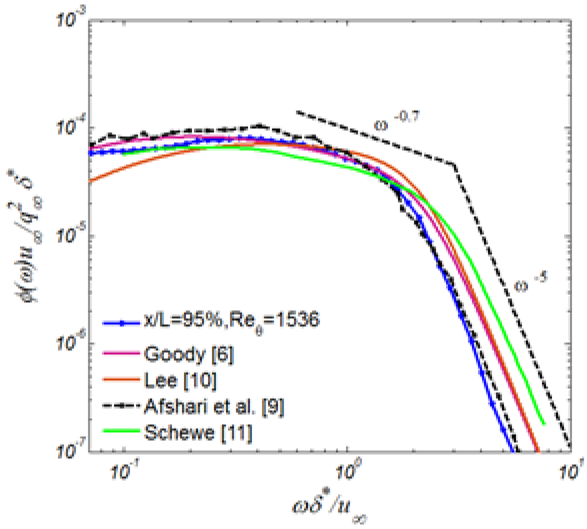

Fig. 2. Surface pressure spectra normalized with outer variables of the turbulence boundary layer at x/L = 95%

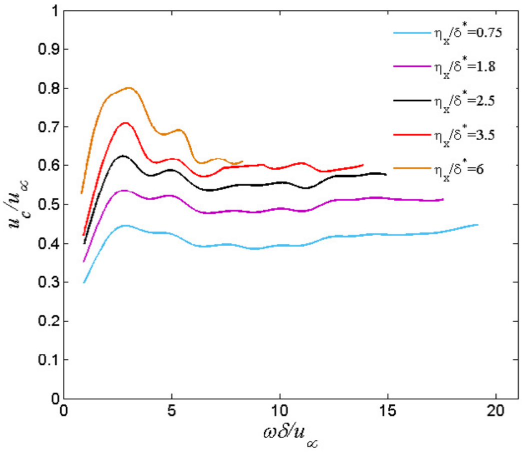

Fig. 3. Variation of eddy convection velocity with and with $\omega\delta/u_\infty$ a distance between streamwise probes

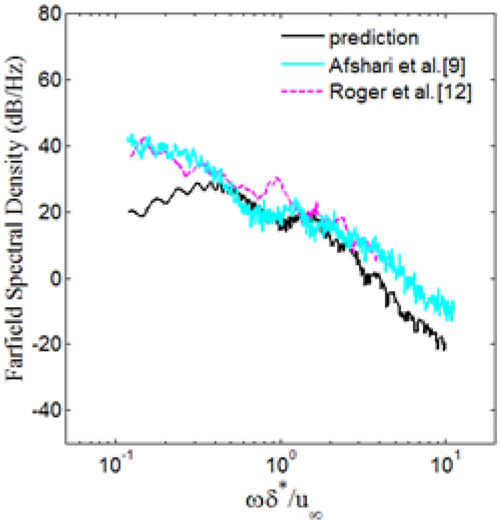

Fig. 4. Far-field pressure spectral density predicted by analytical Roger et.al. [12] model in comparison with experimental results [9, 12] as a function of no dimensional frequency$\omega\delta^*/u_\infty$ at Z =58.5 mm

2. METHODOLOGY

The current study investigates the flow of a turbulent boundary layer over a flat plate of 300 mm chord, with a wetted span of 40 mm. The domain stretches 30 mm in the wall-normal direction. At a free-stream Mach number of 0.06, the Reynolds number based on the flat plate length is 4×10^5. The boundary layer thickness at the inlet boundary selected to be 5-mm. The recycling plane of the Lund [8] model located at $48\delta_0$ downstream of the inlet boundary was used as the inflow generation. This greatly reduces the computational demands. At the outlet and top of the computational domain, Neumann boundary conditions for velocity components are used. The wall modeled with a no-slip condition. Both sides of the domain are considered periodic to simulate an infinite span. Regarding pressure boundary conditions, the pressure on the top boundary is fixed, whereas all other boundaries are modeled using a zero-gradient condition.

The domain is discretized in 400×80×120 cells, resulting in Δx^+=38, Δy^+_{wall}<1 and Δz^+=12. As shown in Fig. 1, an L-shaped array of probes is defined over the flat plate surface to obtain unsteady pressure fluctuations in both streamwise and spanwise directions.

3. RESULTS AND DISCUSSION

Fig. 2 shows the surface pressure Power Spectral Density (PSD) near the trailing edge normalized with outer scaling parameters of the boundary layer in comparison with the results of [6, 9-11]. As may be seen, PSD spectra decay as $\omega^{-0.7}$ and ω^{-5} in the mid and high-frequency ranges, respectively.

Fig. 3 shows the ratio of eddy convection velocity for various streamwise spacing for a free-stream velocity of 20 m/s. As may be seen, the eddy convection velocity increases with increasing streamwise spacing between the probes. Finally, Roger et al. [12] analytical model, which uses surface pressure spectra, the spanwise length scale of the surface pressure fluctuations and eddy convection velocity as the input parameters, is used for predicting the far-field spectra at z=585 mm as presented in Fig. 4. Results show that despite the deviation of analytical prediction from experimental results of [9, 12], the analytical model adequately predicts both magnitudes and the general trend of the far-field noise. Deviation at low-frequency range is due to the utilization of tripping for turbulent boundary layer generation and hence thickening the boundary layer. In the high-frequency range, the deviation is due to the result of applying Corcos [7] correction in Ref. [9, 12].

4. CONCLUSIONS

In the present study, the LES approach used to simulate incompressible flow over a flat plate to directly determine the frequency-dependent parameters affecting far-field noise prediction under a fully developed turbulent boundary-layer of low-Mach-number flow. An L-shaped array of probes defined over the flat plate surface to capture unsteady pressure fluctuations for determining the surface pressure power spectral density, the spanwise length scale of the SPFs and eddy convection velocity in the TE region. The results show that these parameters provide useful information regarding the flow field structure in the turbulent boundary layer. Furthermore, the results confirm the effectiveness of the numerical algorithm used in the present study for the prediction of far-field turbulent boundary layer trailing edge noise.

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