21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

A RANS-based Solution for Trailing-Edge Noise Including Adverse Pressure Gradient Effect

L. Chen[1], R. Leung[2] and P. Joseph[3]

[1]Maritime Division, DST
506 Lorimer Street VIC 3207, Australia

[2]Dstl, Portsdwon West,

Portsdown Hill Road Fareham, Hampshire, PO17 6AD, UK

[3]Institute of Sound and Vibration Research
University of Southampton, Highfield, Southampton, SO17 1BJ UK

Abstract

Trailing-edge noise is of great interest to many industries. It constitutes an important part of flow-induced noise, particularly for low Mach number flows. The turbulent flow over a hydro/air-foil and the associated sound generation is a complex phenomenon, particularly when flows are subjected to an Adverse Pressure Gradient (APG) that could be caused by an angle of attack (AOA) greater than zero. An APG can significantly change the flow characteristics and affect the sound generation.

Trailing-edge noise can be predicted by either Computational Fluid Dynamics (CFD) or empirical models. Some effort in improving the existing empirical models for trailing-edge noise to account for APG influence can be found in the literature. A model based on CFD for calculating the surface pressure fluctuation and an acoustic analogy for sound radiation has been applied successfully to the attached flow. The ability of this model to predict the trailing edge noise for flows subject to an APG is addressed in this paper.

In this paper, the trailing-edge noise from a 2D NACA0012 aerofoil at various Reynold numbers up to 6x10^5 and two angles of attack, 6.25º and 2.8º, are predicted using the RANS-based model previously developed for the attached flow. The predicted results are compared with experimental measurements. The calculated surface pressure spectra and radiated noise are in good agreement with the experimental data. It has found that the model previously developed for the attached flow can be directly applied to a flow subjected to an APG without modification.

Introduction

Trailing-edge noise is of great interest to many industries. It constitutes an important part of flow-induced noise particularly for low Mach number flows. Understanding the noise generation mechanism and how to predict it has been the subject of intensive research (such as [1], [2] and [3]). The turbulent flow over a hydro/air-foil and the associated sound generation is a complex phenomenon due to the rich physics associated with turbulence and sound scattering, particularly when flows are under the influence of an Adverse Pressure Gradient (APG) that could be caused by an angle of attack greater than zero. An APG can significantly change the flow characteristics and affect sound generation (e.g. [4] and [5]).

To predict trailing-edge noise induced by turbulent flows, Lighthill's quadrupole sources [6] can be related to the surface pressure fluctuation beneath the turbulent boundary layer through a proper Green's function [3]. The trailing-edge noise is proportional to a wave number spectrum of surface pressure fluctuations. Under the frozen phase assumption, the wave number spectrum can be written as the product of a point surface pressure spectrum and the pressure correlation scales in three dimensions. Thus, it is critical to be able to model the point surface pressure accurately if the trailing-edge noise is to be predicted.

Research on surface pressure fluctuation beneath a turbulent boundary layer has been very active over decades (such as [7], [8] and [9]). Previously, the estimations relied heavily on empirical expressions. For example Goody [8] and Blake [9] derived their empirical models based on the experimental data measured by different groups. In those models, the effect of Reynolds number and frequency were included explicitly, but none of them has explicitly considered the effect of APG on the pressure spectra. Recently, Rozenberg and Robert [10] reported a modified Goody model [8] to explicitly account for the effect of APG. The model showed a significant improvement for the cases studied.

Computational Fluid Dynamics (CFD) has been used to model the surface pressure spectrum for trailing-edge noise predictions. For example, Chen and MacGillivray [11], Lee, Farabee & Blake [12] and Peltier & Hambric [13] all estimated the surface pressure spectra directly from the turbulence statistics calculated using CFD. These CFD-based models have been applied successfully to attached flows or flows with a weak APG. There are few reports on their application to the flows under a strong effect of APG. The aim of this study is to evaluate the capability of the Reynolds-Averaged-Navier-Stokes (RANS)-based trailing-edge model of Chen and MacGillivray [11] for flows under the influence of APG.

Modelling surface pressure spectrum and trailing-edge noise

Sound generated by turbulent flow over a large surface has quadrupole radiation characteristics and is weak. However, with a termination of the surface, such as a trailing edge, the turbulence-induced noise radiates with a dipolar pattern, allowing turbulence eddies with scales much less than the acoustic wave lengths to radiate more efficiently. Such trailing edge noise is important, particularly for a low Mach number flow.

For the trailing edge of an aerofoil that is of a semi-infinite chord with a finite span-wise dimension L as shown in Figure 1, the spectrum of the trailing edge noise,Φ^{rad} ,can be expressed in terms of the point wall pressure Φ_{pp} and the span-wise correlation length scale of pressure fluctuation, l_3 , as

$$\Phi^{rad} = \Phi^{semi} \left| G_N \right|^2 \tag{1}$$

$$\Phi^{semi}(\mathbf{y}, \omega) = \frac{\omega L \sin^2(\theta/2) \sin\psi}{2\pi c_0 |\mathbf{y}|^2} l_3 \phi_{pp}(\omega) \tag{2}$$

where ω is the radian frequency and c_0 is the sound speed in fluid. $\mathbf{y}(y_1, y_2, y_3)$ is observation coordinates. G_N is a normalised green function to account for the multi-scattering from the leading edge of the foil.

With decomposing the flow variables velocity, u and pressure p into the mean and fluctuating components, the equation for the surface pressure fluctuation can be derived from the Navier-Stokes equation as a function of mean flow and turbulence statistics as

$$\phi_{pp}(\omega) = f\left(\frac{\partial \overline{u_1}}{\partial y_1}, k, f_{aniso}, \frac{T_T}{T_{M,max}}, \delta^*, \Lambda_2\right) \tag{3}$$

$\overline{u_1}$ is stream-wise mean velocity, k is turbulent kinetic energy and δ^* is displacement thickness. T_T and $T_{M\,max}$ are the turbulence-turbulence interaction and the mean-shear-turbulence interaction respectively. Λ_2 is the correlation length of vertical velocity fluctuation, u_2'. The anisotropic nature of the flow is accounted for by means of f_{aniso} as

$$\overline{u_2'^2} = \frac{2}{3} k f_{\text{aniso}} \tag{4}$$

The vertical velocity fluctuation, the gradient of the streamwise velocity, the turbulent-turbulent interaction and the combined turbulence-turbulence and mean-shear-turbulence interaction are modelled based on the solution of CFD simulations. The details of the model can be found in [11].

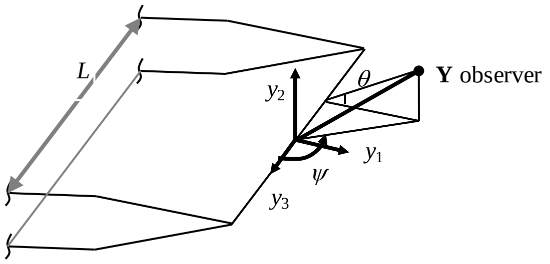


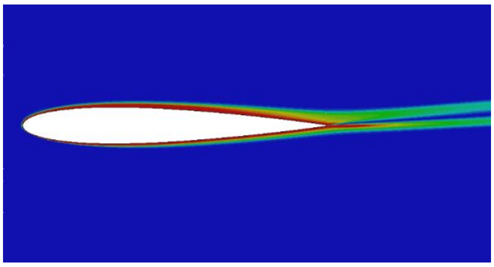
Figure 1 – Coordinates defining trailing edge noise from a half-foil

Simulating flows around NACA0012 at AOA=6.25° and 2.8°

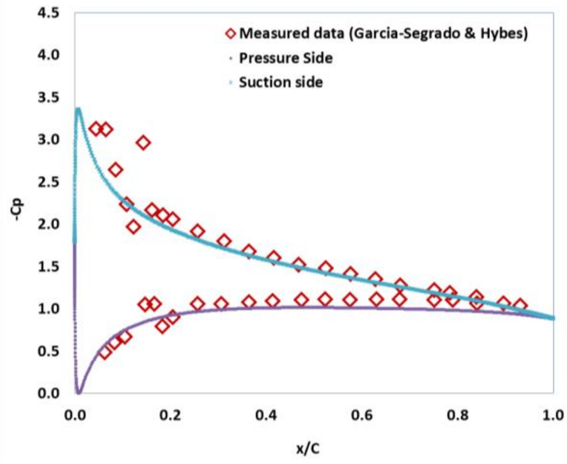
Flows around a NACA 0012 aerofoil at the angle of attack AOA = 2.28° with Reynolds number of $\mathrm{Re} = 4 \times 10^5$ are modelled using RANS equations. The turbulence model used in those simulations is the $k - \omega$ SST model. The simulation was carried out using FLUENT in ANSYS15. The details regarding the numerical model, including the CFD model validation, can be found in [11]. As a further validation of the CFD, the measurement flow field of Garcia-Sagrado and Hynes [4] at AOA=6.25° was simulated.

The APG effect is normally expressed as an acceleration parameter, K, that is a function of stream-wise velocity gradient, fluid viscosity and flow speed. For AOA=6.25°, the acceleration parameter estimated by CFD at the middle section was $K \times 10^6 = -0.015$ for the suction surface and $K \times 10^6 = 0.015$ for the pressure surface. The acceleration parameter calculated in the experiment of Garcia-Sagrado and Hynes in [4] is -0.99. The cause of the discrepancy will be the subject of a further investigation. For AOA=2.8°, the estimated acceleration parameter at the suction side is -0.012 and the pressure side is 0.012.

The contour of the vorticity in the boundary layer and the pressure coefficient distribution are shown in Figures 2a and 2b, respectively. An antisymmetric flow field, due to the angle of attack, is depicted. The predicted pressure coefficient distributions agree well with the experimental data of Garcia-Sagrado and Hynes [4], demonstrating the accuracy of the CFD simulations.



(a) Vorticity contours



(b) comparison of pressure coefficient

Figure 2 Flow characteristics for a NACA0012 at $Re = 4 \times 10^5$ and AOA=6.25°: (a) vorticity contours and (b) comparison between predicted and measured pressure coefficient

Measuring pressure fluctuation and far-field noise

Surface pressure fluctuation and far-field flow-induced noise measurements for a NACA0012 at AOA=0 and 2.8° were made in the ISVR open-jet wind tunnel facility within the anechoic chamber shown in Figure 3. The chamber is of dimension 8m × 8m × 8m, and the jet was generated through a series of silencers to ensure a quiet, uniform and low-turbulence flow with a nozzle of dimension 0.15m × 0.45m. A detailed sketch of the setup is presented by Chong [14]. The chord of the NACA0012 tested was 150mm. The foil was mounted between two side plates. The surface pressure fluctuations were measured by microphones connected to surface pressure taps. The surface pressure fluctuations were measured at four locations near the trailing edge: two were at 95% of chord and another two at 89% of the chord with 5mm separation in the span-wise direction. The far-field noise measurements were made with 11 half-inch condenser microphones (B&K type 4189) which were located radially at a distance of 1.2 m from the mid-span of the aerofoil. These microphones were placed at emission angles between 40° to 140° measured relative to downstream of the jet axis.

Measurements are made for a sampling period of 10s duration at sampling frequency of 50 KHz. Based on previous experience, the far-field noise measured was trailing-edge noise dominated.

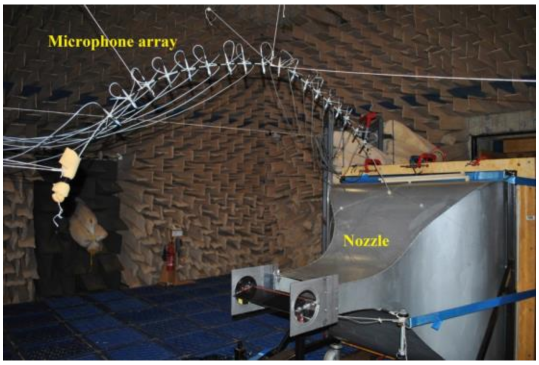


Figure 3 Experimental setup

Results and discussion

Comparison of surface pressure

For AOA=2.8°, the predicted surface pressure spectra on both sides of the aerofoil at different locations are plotted against experimental measurements in Figure 4. It can be seen that the predicted pressure spectrums at either suction-side or pressure-side at $x_1/c = 0.89$ agree very well with the measurement over the frequency range of 300 to 5000 Hz. At $x_1/c = 0.95$, a ±3dB deviation from the measurements are observed on either pressure-side or the suction-side. For the pressure side, the model over-predicts by 2 to 5 dB over all frequencies compared with the measurements, and for the suction side, the model over-predicts by 2 dB at frequencies lower than 1000Hz and under-predicts over the frequency range of 1000 to 8000Hz. In general, the point surface pressure spectrum changes near the trailing-edge, leading to an increase at low frequencies and a decrease at high frequencies. This is consistent with the measurement of Garcia-Sagrado and Hynes in [4]. However, the current measured surface pressure spectrums only change slightly with a change of location. The predicted surface pressure spectra levels on the pressure side are higher than those on the suction side at $x_1/c = 0.95$. Therefore, the predicted trailing-edge noise will be dominated by the surface pressure fluctuation.

For the case of AOA=6.25°, the predicted surface pressure spectrum is normalised using both inner- and outer- variables to show the characteristics of the spectrum using different scaling. The inner variables are wall shear stress, τ and shear velocity u_τ. The outer variables are displacement boundary layer thickness, δ^* and convection speed U_e. The results are compared with the experimental data of Garcia-Sagrado and Hynes [4] and the empirical models of Goody [8] and Blake [9]. The comparisons for the pressure spectrum normalised by the inner variables are shown in Figure 5a. It can be seen that the RANS-based model in [11] provides the most satisfactory result when comparing with experimental data. The Blake model [9] provides reasonable predictions at high frequencies but clearly underestimates at low frequencies. Goody's model does not provide satisfactory results for all frequencies. The predicted pressure spectrum normalised by the outer variables is depicted in Figure 5b. Again, the RANS-based model produces excellent agreement with the experimental data. The RANS-based model over-predicts by around 5dB the inner variable based pressure spectrum at the normalised frequencies greater than one and under-predicts by 3dB the outer variable based pressure spectrum at the normalised frequencies lower than 0.3. Overall, the RANS-based model yields a better agreement with the experimental data if the pressure spectrum is normalised by the outer variables. It should be noted that the boundary layer displacement thickness and wall shear stress required by the two empirical models are based on the CFD solution.

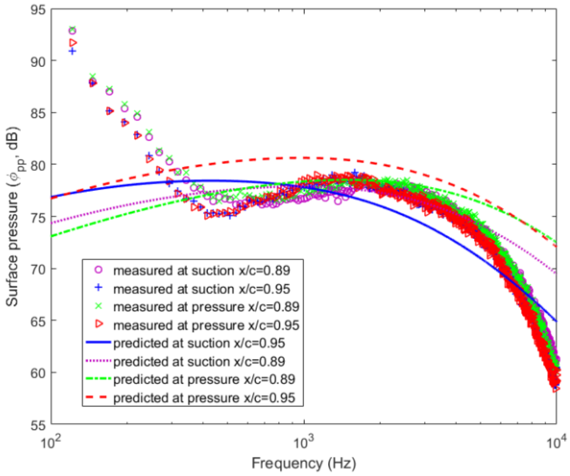
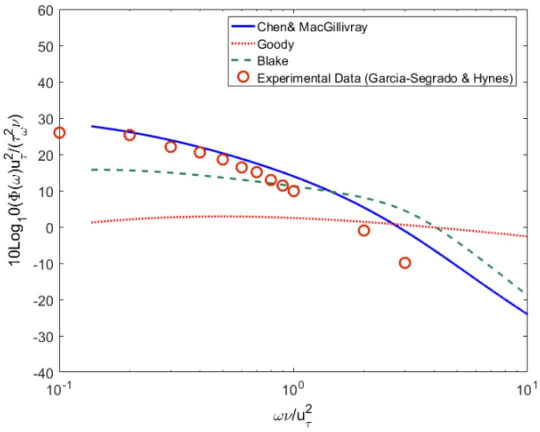


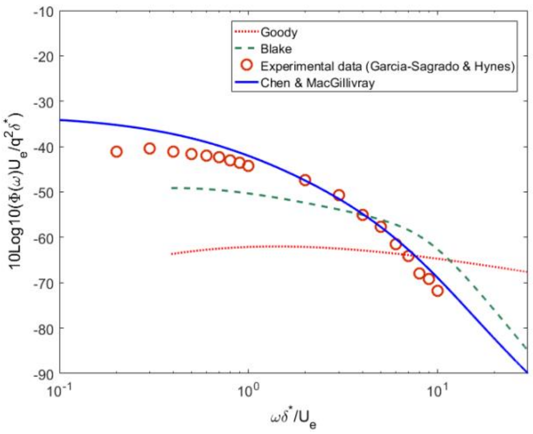
Figure 4 Comparison between predicted pressure spectrums and experimental data for Re $= 4 \times 10^5$ at AOA=2.8° (dB re 20 μPa)

Comparison of sound pressure level

The predicted sound pressure levels are compared with the measurements conducted at ISVR. The comparison for AOA=2.8° is shown in Figure 6a; the comparison for AOA=0° is given in Figure 6b. For both cases, the predicted trailing edge noises are in good agreement with the measurements over the frequency range 300 Hz to 10 kHz. It can be seen that with an increase in AOA, the peaks of the trailing edge noise shift to lower frequencies and the level increases by 2dB. The high frequency fall-off portion is unchanged. This finding is consistent with that of Hutcheson and Brooks [15].

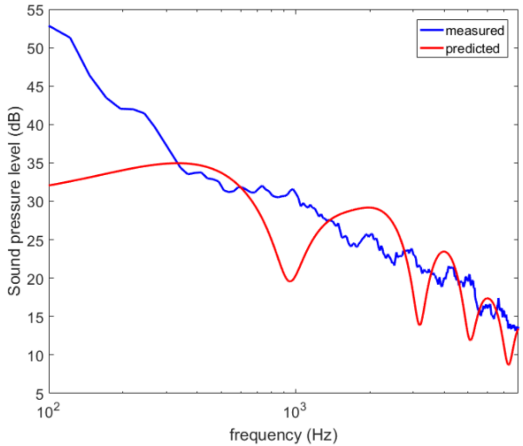


(a) Normalised by inner variables

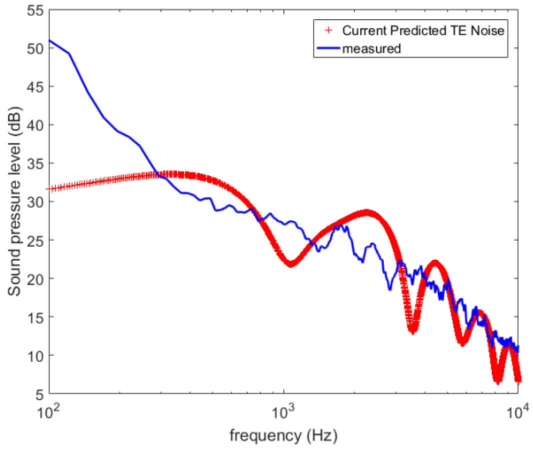


(b) Normalised by outer variables

Figure 5 Comparison between predicted pressure spectrums (suction side), experimental data and other empirical models for $Re = 4 \times 10^5$ at AOA=6.25°, (a) normalised by the inn-variables, (b) normalised by the outer-variables.



(a) AOA=2.8°



(b) AOA=0°

Figure 6 Comparison between predicted and measured trailing-edge noise: (a) AOA=2.8°, (b) AOA=0° (dB re 20 μPa)

Conclusions

The RANS-based trailing-edge noise model has been successfully applied to the turbulent flows over a NACA0012 aerofoil at Reynolds number of 4×10^5 with an angle of attack of 6.25° and 2.8° respectively. The flows are subjected to an Adverse Pressure Gradient. The predicted surface pressure spectrums for two cases and the predicted far field trailing edge noise are in good agreement with experimental data. It can be concluded that the RANS-based trailing edge noise model developed previously is capable of providing accurate results for flows under the influence of APG without the requirement of any modification.

References

[1] Sandberg, R & Sandham, N.D., "Direct numerical simulation of turbulent flow past a trailing edge and the associated noise generation", *Journal of Fluid Mechanics*, Vol. 596, 2008, pp. 353-385.

[2] Lau, A.S.H., Kim, J.W., Hurault, J., Vronsky, T. and Joseph, P., Aerofoil trailing-edge noise prediction models for wind turbine applications, *Wind Energy*, 2017, DOI:10.1002/we.

[3] Gloerfelt, X., "The link between wall pressure spectra and radiated sound from turbulent boundary layer", *AIAA paper* 2010-3904, 2010.

[4] Garcia-Sagrado, A. and Hynes, T. "Wall pressure sources near an airfoil trailing edge under turbulent boundary layer", *Journal of Fluid and Structures*, Vol. 20, pp 3-34, 2012

[5] Shin, JH and Song SJ, "Pressure gradient effects on smooth- and rough-surface turbulent boundary layers – part II: adverse pressure gradient", *Journal of Fluids Engineering*, Vol. 137, pp. 011204-1-7, 2015.

[6] Lighthill, M.J., "On sound generated aerodynamically. Part I: general theory", *Proceedings of Royal Society London A* Vol. 211, 1952, pp. 564-587.

[7] Largeau, J.F. & Moriniere V., "Wall pressure fluctuations and topology in separated flows over a forward-facing step", *Experiments in Fluids*, Vol. 42, 2007, pp. 21-40, DOI 10.1007/s00348-006-0215-9.

[8] Goody, M., "Empirical spectral model of surface pressure fluctuations", *AIAA Journal*, Vol. 42, No. 9, 2004, pp. 1788.

[9] Blake, W.K., "Turbulent boundary-layer wall-pressure fluctuations on smooth and rough walls", *Journal of Fluid Mechanics*., Vo. 44, 1970, pp. 637-660.

[10] Rozenberg, Y. and Robert, G. "Wall-pressure spectral model including the adverse pressure gradient effects", *AIAA Journal*, Vol. 50(10), pp. 2168-2180, 2012.

[11] Chen, L. and MacGillivray, I., "Prediction of Trailing-edge Noise based Reynolds-Averaged Navier-Stokes Solution", *AIAA Journal*, Vol. 52(14) pp. 2673-2681, 2014.

[12] Lee,Y-T., Farabee, T.M. & Blake W.K., "Turbulence effects of wall-pressure fluctuations for reattached flow", *Computers & Fluids*, Vol. 38, No. 5, 2009, pp. 1033-1041.

[13] Peltier, L.J. and Hambric, S.A., "Estimating turbulent-boundary-layer wall pressure spectra from CFD RANS solutions", *Journal of Fluids and Structures*, Vol. 23, 2007, pp. 920-937.

[14] Chong, T.P., Joseph, P.F. and Davies, P.O.A.L., "Design and performance of an open jet wind tunnel for aero-acoustic measurement", *Applied Acoustics*, 70(4), pp. 605-614, 2009.

[15] Hutcheson, F.V. and Brooks T.F., "Effect of angle of attack and velocity on trailing edge noise", *42nd AIAA aerospace Sciences Meeting and Exhibit*, Reno, Vevada, AIAA2004-1031, 2004.