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# COMPARISON OF AEROACOUSTIC PREDICTIONS OF TURBULENT TRAILING EDGE NOISE USING THREE DIFFERENT FLOW SOLUTIONS

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## Abstract

Noise generated by turbulent flow past a sharp edge is important in the design of a variety of applications such as aircraft and wind turbines. It is therefore useful to have predictive methods that can capture the effects of subtle design changes on the flow and resulting radiated noise. In this paper, such a methodology is presented and used to predict noise from a sharp-edged strut with a turbulent boundary layer. The method is unique because it combines mean flow data from a Reynolds Averaged Navier Stokes (RANS) solution with statistical models of the turbulence to form acoustic source terms for an analytical acoustic model. Three different CFD codes (OpenFOAM, STAR-CCM+ and Fluent) are used to carry out the flow calculations, and two of the solutions are used as input to the noise prediction model. The resulting noise predictions are critically compared against each other and also with experimental data. The differences are highlighted to illustrate the sensitivity of the acoustic predictions to the RANS solution.

## Introduction

Trailing edge noise is an undesired feature in a range of applications, including (but not limited to) aircraft and wind turbines. It is therefore useful to have predictive methods that can capture the effects of subtle design changes on the flow and resulting radiated noise. Empirical models, such as the BPM model [4], are often used due to their computational efficiency; however, these methods are based on global flow parameters (generally displacement thickness and mean flow velocity), and hence cannot capture the effects of subtle design changes in the resulting noise spectrum. Moreover, they do not perform well in low to moderate Reynolds numbers flows [10].

Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) can be used to calculate the radiated noise directly [12], or to provide the time varying data required to assemble the noise sources for noise calculations using Linearized Euler Equations (LEE), or an acoustic analogy technique. However, the computational requirements of DNS and LES are very large, making their use cumbersome for the design of low noise airfoils, where many design variations need to be evaluated in a timely manner.

As the solution of the Reynolds Averaged Navier-Stokes (RANS) equations is a well established tool for aerodynamic design, and it poses less stringent computational demands than DNS or LES, RANS-based trailing edge noise prediction methods are highly desirable. However, RANS does not provide enough information to perform noise calculations directly, so a model for the turbulent sources is required. A possible approach is to use a model for the surface pressure spectrum near the trailing edge, based on the mean flow statistics provided by a RANS solution, and use the theory of Amiet [3] to calculate the far field noise. Different surface pressure spectrum models have been proposed and used for trailing edge noise calculations with mixed results [9]; however, these models assume homogenous turbulence in the spanwise and chordwise directions, a condition which is not satisfied in boundary layers with strong adverse pressure gradients.

A steady RANS solution can be used to obtain one-point flow statistics. A synthetic turbulence field, which matches these flow statistics, can be stochastically generated and used as the source term for a Computational Aero-Acoustics (CAA) calculation. This method is called the Stochastic Noise Generation and Radiation (SNGR) method. The advantage of this method is that it can be applied not only to trailing Edge (TE) noise predictions [6], but also to other aeroacoustic problems, such as landing gear noise [5]. The main disadvantage of the SNGR method is the large computational time and memory requirements, as it needs to create and store the time varying velocity fields for use with an LEE solver.

In this paper, a RANS-based Statistical Noise Model (RSNM) is used to calculate the sound radiated by the trailing edge of a sharp-edged symmetric strut. The method is unique because it combines mean flow data from a RANS solution with statistical models of the turbulence to form acoustic source terms for an analytical acoustic model. The mean flow data were provided by three different flow solvers (OpenFOAM, STAR-CCM+ and Fluent), and the main aim of the paper is to assess the sensitivity of the acoustic predictions to the RANS solution.

## Noise Prediction Method

The noise prediction model is based on a statistical model of the turbulent velocity cross-spectrum between two points in the boundary layer (i.e. the noise source) and the use of this information as an input to a Green's function solution for airfoil trailing edge far-field noise [7]. A Computational Fluid Dynamics (CFD) RANS solution is used to calculate the mean velocity, turbulent kinetic energy and dissipation in the vicinity of the trailing edge. This information is used to estimate the turbulence cross spectrum, which is used to calculate the noise via a summation procedure. For brevity, only the final equations are presented here. For a full derivation of the model see [2].

The power spectral density at an observer position $\mathbf{x}$ in the far field can be calculated as,

$$S(\mathbf{x},\omega) = \sum_{\mathrm{V}(\mathbf{y_1})} \sum_{\mathrm{V}(\mathbf{y_2})} \Psi\ \Phi F(\mathbf{y_1}) F(\mathbf{y_2}) \mathrm{dV}(\mathbf{y_2}) \mathrm{dV}(\mathbf{y_1}) \qquad (1)$$

where $\mathrm{V}(\mathbf{y_1})$ and $\mathrm{V}(\mathbf{y_2})$ are the volume elements containing the acoustic sources with vector locations $\mathbf{y_1}$ and $\mathbf{y_2}$, respectively, and $\Psi = \Psi(\mathbf{y_1},\mathbf{y_2},\omega)$ and $\Phi = \Phi(\mathbf{y_1},\mathbf{y_2},\omega)$ are defined as:

$$\Psi(\mathbf{y_1},\mathbf{y_2},\omega) = \frac{2\rho_0^2\omega\sin\phi\cos^2\frac{\theta}{2}}{\pi c_0 r_0(\mathbf{y_1})^{3/2} r_0(\mathbf{y_2})^{3/2} R(\mathbf{y_1})R(\mathbf{y_2})} \quad (2)$$

where $\rho_0$ is the density of air, $\omega$ is the angular frequency, $c_0$ is the speed of sound, $R$ is the distance between the source and the observer, and the angle $\phi$ is derived from:

$$\sin\phi = \frac{r}{\sqrt{r^2+(z-z_0)^2}} \quad (3)$$

where r is the distance from the observer to the trailing edge, and $z-z_0$ is the distance in the spanwise direction between the observer and the acoustic source (see Figure 1). The mean flow function $F(\mathbf{y})$ is defined as,

$$F(\mathbf{y}) = \left\{ (\bar{U}_r - f_a\bar{U}_\theta)\cos(\frac{1}{2}\theta_0) - (f_a\bar{U}_r + \bar{U}_\theta)\sin(\frac{1}{2}\theta_0) \right\} \quad (4)$$

where $\bar{U}$ is the mean flow velocity, $\theta_0$ is the angle between the source and the trailing edge plane, $f_a$ is an anisotropy factor ($f_a = 1$ for isotropic turbulence), and

$$\Phi(\mathbf{y_1},\mathbf{y_2},\omega) = \frac{A\sqrt{\pi}}{\omega_s}u_s^2\exp\left(-\frac{|\eta|^2}{\ell_s^2}\right)\exp\left(-\frac{\omega^2}{4\omega_s^2}\right)L_z \quad (5)$$

is the turbulence velocity cross spectrum, where $\eta = \mathbf{y_1} - \mathbf{y_2}$ and $A = 1/158$ is an empirical parameter (see [2]), and

$$L_z = \begin{cases} \frac{2.1M_c c_0}{\omega L} & \text{if } L_z \leq 1, \\ 1 & \text{if } L_z > 1. \end{cases} \quad (6)$$

where $M_c$ is the convective Mach number of the eddies, $\omega$ is the angular frequency and $L$ is the wetted span of the airfoil. To link this model to a CFD solution (i.e. RANS calculated turbulence data), the following definitions are used [11],

$$u_s = \sqrt{2k/3}, \;\; \omega_s = 2\pi/\tau_s, \;\; \tau_s = c_\tau k/\varepsilon, \;\; \ell_s = c_\ell k^{3/2}/\varepsilon \quad (7)$$

where $k$ is the turbulent kinetic energy, $\varepsilon$ is the turbulent dissipation, $c_\ell = 0.11$ and $c_\tau = 0.12U_\infty + 0.73$, where $U_\infty$ is the freestream velocity, are semi-empirical parameters, which were determined based on a series of NACA 0012 cases [2]. To take into account leading edge back-scattering, the resulting spectrum is also multiplied by the multiple-scattering correction of Howe [8].

### RANS Simulation Settings

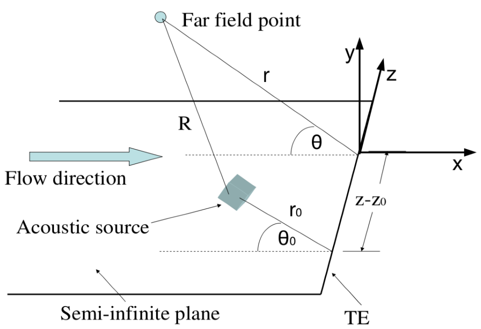


Figure 1: Geometry of noise generation simulations. This cylindrical coordinate system centered at the trailing edge is used in the definition of the acoustic model

The simulations were run using three different CFD packages, namely OpenFOAM, STAR-CCM+ and Fluent, each one with a different mesh and numerical settings and created by different individuals. For the OpenFOAM computations, the mesh had 426,000 cells, with a $y+ = 2.34$ at the trailing edge. This resolution was found sufficient to provide a converged solution. Details of the grid refinement study can be found in [1]. Closure of the RANS equations was provided by the $k-\omega$ SST model with first order convection. Wall functions were used for $k$, $\omega$ and for the eddy viscosity $\nu_t$.

For the Star-CCM+ computations, the mesh consisted of 1,790,681 cells, the turbulence model is $k-\omega$ SST with 2nd order convection, with the Realizability-option set to Durbin-Scale-Limiter and Low-Reynolds damping modification was turned on. A Hybrid Wall Treatment (HWT) was used.

For the Fluent computations, the mesh consisted of 460,000 cells, and the turbulent model used was the transition $k-\omega$ SST with a near-wall treatment model, which combines a two-layer model with an enhanced wall function. Table 1 provides a summary of the CFD details. A quantitative grid-refinement study was not performed for the Fluent and Star-CCM+ computations.

Table 1: Grid properties and wall treatment for all CFD calculations.

| CFD solution | No. of cells | $y+$ at TE | Wall treatment |
|---|---|---|---|
| Star-CCM+ | 1,790,681 | 1.0 | HWT |
| Fluent | 460,000 | 0.03 | wall function |
| OpenFOAM | 426,000 | 2.34 | wall function |

### Flow Results

To provide a measure of validation, the turbulence intensity (Ti) and mean velocity profiles obtained from the CFD calculations are compared to the experimental data of Moreau et. al. [10], at a location 0.7 mm downstream of the trailing edge. As Figure 2 shows, the mean velocity profile, $U/U_\infty$, is relatively well predicted by all CFD packages. The Fluent solution shows a good agreement in the inner boundary layer, but starts to depart from the experimental curve at $y/c \approx 0.01$, where $c$ is the airfoil chord, showing a thinner boundary layer than the experimental profile. The Star-CCM+ mean velocity prediction underpredicts the experimental data for $y/c < 0.006$, then agrees very well with the experimental curve for $0.006 < y/c < 0.012$, and then departs from the experimental profile, following the Fluent prediction closely. The OpenFOAM mean velocity profile underpredicts the experimental curve for $y/c \leq 0.02$, but agrees very well with the experimental profile for $y/c > 0.02$.

Figure 3 shows the turbulence intensity curves. The agreement between CFD and experiment is not as good as for the mean velocity profiles. Notably, the Star-CCM+ curve underpredicts the turbulence intensity values, and reaches the free stream value much sooner than the experiment. Similarly, the Fluent curve decays much faster than the experimental curve, and the free stream value is much lower than what is observed in the experimental data. However, the location and magnitude of the peak are well captured. The OpenFOAM prediction shows the correct magnitude of the peak, but locates it further out in the boundary layer, and overpredicts the turbulence intensity in the region up to $y/c \approx 0.2$, and then underpredicts it for $0.02 < y/c < 0.04$.

Figure 4 shows the turbulence dissipation ($\omega$) obtained form the RANS simulations. Since no experimental data are available for this quantity, the RANS data are compared to each other. There is good agreement between the Star-CCM+ and OpenFOAM solutions for $y/c \leq 0.02$. The data obtained with Fluent shows much lower levels than the other two curves for $y/c \leq 0.005$, and then agrees well with the other two curves for $0.005 \leq y/c \leq 0.025$.

To evaluate the quality of the RANS solutions, an error estimate was calculated using using the following expression:

$$\text{error} = 100 \times \frac{1}{N} \sum \frac{|\phi_{ei} - \phi_i|}{\phi_{ei}} \tag{8}$$

where $\phi_{ei}$ and $\phi_i$ are the experimental and numerical values of a given parameter, respectively, and $N = 67$ is the number of samples in the curve. The CFD data were interpolated to match the sample locations of the experimental curve, and the error calculation was performed for $0 \leq y/c \leq 0.04$. The results are presented in table 2.

Table 2: Percentage error between experimental and numerical mean velocity and turbulence intensity at 0.7 mm downstream of the trailing edge.

| CFD solution | Ti error (%) | $U/U_\infty$ error (%) |
|---|---|---|
| Star-CCM+ | 31.04 | 4.78 |
| Fluent | 34.56 | 3.53 |
| OpenFOAM | 8.29 | 4.89 |

The boundary layer thickness, $\delta$, was calculated from the turbulence intensity profiles, and was defined as the location in the outer boundary layer where:

$$\frac{\partial Ti}{\partial (y/c)} \leq 0.1 \tag{9}$$

The boundary layer thickness values obtained with this approach are shown in Table 3.

Table 3: Turbulent-intensity-based boundary layer thickness,$\delta$, calculated using the turbulence intensity profiles at 0.7 mm downstream of the trailing edge.

| Star-CCM+ | Fluent | OpenFOAM | Moreau et.al. |
|---|---|---|---|
| $\delta$ =5.7 mm | $\delta$ = 6.1 mm | $\delta$ = 7.9 mm | $\delta$ = 8.6 mm |

### Acoustic Results

The RANS data required for RSNM calculations was sampled in a domain extending one boundary layer thickness upstream and downstream of the trailing edge, and of a height of one boundary layer thickness, as shown in Figure 5. The boundary layer thickness values used for each RANS solution are shown in table 3. Each side of the airfoil is assumed to radiate sound independently of the other, so that the resulting power spectral density $S_{total}$ can be calculated as

$$S_{total} = S_{side1} + S_{side2} = S_{side1} + 3dB \tag{10}$$

Acoustic predictions for the Star-CCM+, Fuent and OpenFOAM RANS solutions are shown in Figure 6, using two different values for the length scale parameter $c_\ell$. It can be observed that there is a difference of up 5 dB in the lower frequencies between the noise predictions using Fluent and OpenFOAM data, with the prediction based on Star-CCM+ data falling between the other two predictions. This difference decreases as frequency increases. The differences between the acoustic predictions can be atributed to the differences in the predicted turbulent kinetic energy and dissipation. The higher noise levels obtained with the OpenFOAM data are due to the higher levels of turbulent kinetic energy predicted by OpenFOAM in relation to the other two CFD packages.

The predicted levels are much lower than the levels measured experimentally when the value of $c_\ell = 0.11$ is used. This model coefficient was determined using noise data from a NACA 0012 airfoil, and appears not to be valid for the current case. Better agreement with experimental data is obtained when a value of $c_\ell = 0.25$ is used; however, the agreement at the lowest frequencies remains poor. Moreau et. al. [10] suggested that the sudden change in slope upstream of the trailing edge generates a sudden change in pressure gradient, giving rise to large turbulent structures responsible for the large low-frequency content of the spectra. Increasing the value of $c_\ell$ in the model attempts to take into account these large scale structures on noise generation. To achieve better agreement across the entire frequency range, a more sophisticated two-point correlation model for the turbulent flow statistics is needed and this is the focus of future work. It should also be noted that the broadband noise component centered at 1.5 kHz in the experimental spectrum was determined to be facility induced by Moreau et. al. [10], hence the noise model cannot be expected to reproduce this feature.

### Summary and Conclusions

A RANS-based noise prediction model (RSNM) has been applied to a sharp-edged strut with a turbulent boundary layer. The input data for the model were provided by three different CFD packages. The turbulence instensity and mean velocity predicted by the different flow solvers show large differences,

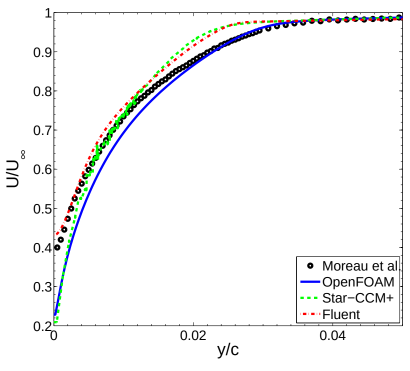


Figure 2: Mean velocity profiles at 0.7 mm downstream of the trailing edge.

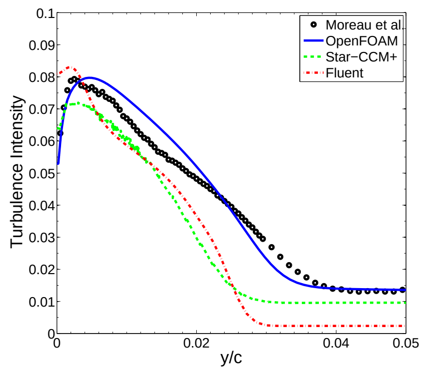


Figure 3: Turbulence intensity profiles at 0.7 mm downstream of the trailing edge.

which are reflected in a difference of up to 5 dB between the different noise predictions. Therefore, it can be concluded that the model is somewhat sensitive to the RANS input data, and hence great care needs to be exercised when generating the flow solution.

Using empirical constants originally determined for a NACA 0012 airfoil, the model under predicted the noise levels. This could be attributed to the flow over the strut's trailing edge containing large turbulent structures that are not present in the boundary layer of the more streamlined NACA 0012 airfoil. The noise predictions can be improved by adjusting the empirical length scale parameter $c_\ell$, which suggests that this parameter has a geometry dependance; however, it appears that a more sophisticated two-point velocity cross-spectrum model is also needed, as the underprediction of the noise spectra may be due to the particular form of the cross-spectrum model used.

It is also possible that the underprediction of the noise spectra is related to the large discrepancies between the experimental and the CFD flow turbulence intensity. This could be verified by using experimental flow data as input to the model, which will form the basis of a future study.


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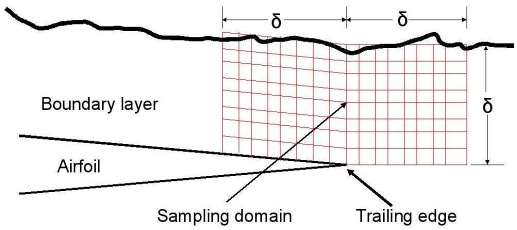


Figure 5: Sampling domain for acoustic sources.

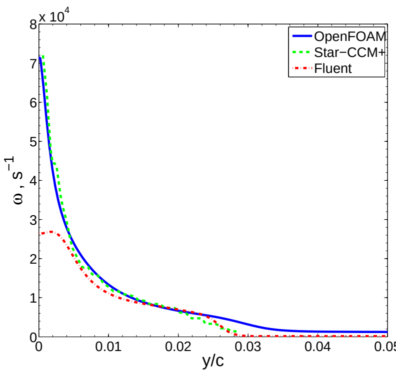


Figure 4: Turbulence dissipation profiles at 0.7 mm downstream of the trailing edge.

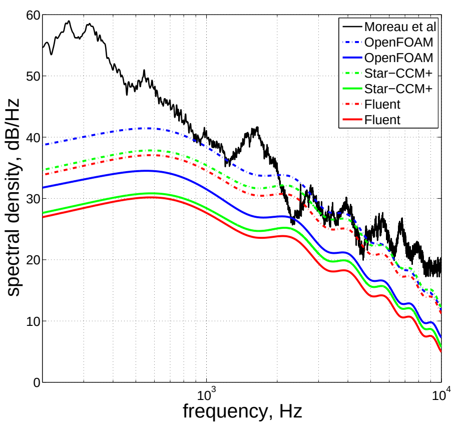


Figure 6: Spectral density at 565 mm over the trailing edge. Solid lines: $c_\ell = 0.11$, dashed lines: $c_\ell = 0.25$