A REVIEW OF AIRFOIL TRAILING EDGE NOISE AND ITS PREDICTION

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ABSTRACT: If technology such as aircraft, submarines and wind turbines are to further reduce their noise emissions, then a better understanding of airfoil trailing edge noise is required. This paper will discuss the physical causes of trailing edge noise and then review the methodologies used over the past couple of decades to model and to estimate trailing edge noise. A comprehensive reference list is given for readers wishing to learn more about this important area of aeroacoutsics. It is shown that one of the major restrictions to further development of prediction methods is a lack of suitable experimental data for validation purposes. Additionally, new turbulence models are needed to improve noise prediction, especially at high frequency.

1. INTRODUCTION

In recent years, engineers and scientists have been able to reduce aeroacoustic and vibroacoustic noise to such an extent that broadband sources are now limiting further noise reduction. This is particularly true for technology that utilise airfoils and airfoil-like shapes that generate broadband noise at the trailing edge (TE). For example, TE noise is an important component of civil aircraft airframe noise during approach and landing. In fact, the long-term goal of the aviation industry is to reduce aircraft noise by 20 dB [1] and the control of TE noise has been identified as critical to achieving this. In naval applications, TE noise from hydrofoils and propellers must be controlled in order to increase the stealthiness of underwater and surface craft [2]. TE noise is also a major noise generation mechanism for the rotor blades of wind turbines [3] and helicopters [4], and limits their use in urban areas. Indeed, the list of applications for which TE noise is significant is extensive and illustrates the universal need for quiet airfoil designs. However, the design of quiet airfoils requires accurate methods to predict TE noise in the far-field.

Predicting TE noise has been an on-going challenge for engineers over the last 30 years. Calculating TE noise is made difficult due to the complexity of the noise source, which is turbulent fluid flow. The complex and stochastic nature of turbulence has forced the development of methods that use simplified turbulence models to calculate noise. Unfortunately, these assumptions hinder the design of new, quiet airfoils due to their limited accuracy. Recent advances in computing power now provide a much better representation of turbulent flow and therefore open the possibility of radically new, quiet airfoil shapes.

It is the goal of this paper to review the various methods of modelling and estimating TE noise and to discuss what challenges remain to develop accurate prediction methods. It is hoped that the paper can be used as a starting point for those wishing to understand and compute TE noise. Key references are provided that can be used to obtain more detail.

2. THE MECHANISM OF TRAILING EDGE NOISE GENERATION

Airfoil self noise occurs when an airfoil shape is placed in an otherwise uniform and steady fluid flow. As in most aeroacoustic noise generation situations, noise is generated by flow unsteadiness. In the case of airfoil self noise, it is the interaction of flow unsteadiness (usually in the form of fluid turbulence) with the surfaces of the airfoil that generates sound. There are a variety of specific noise-generating flows associated with airfoil self noise that are concisely summarised in Ref. [5]. These are: (1) laminar boundary layer – vortex shedding noise; (2) separation stall noise; (3) tip vortex formation noise and (4) TE noise.

Trailing edge noise is caused from the interaction of turbulence with the TE. Fluid turbulence is a term that characterises the irregular flow of air and other fluids past (airfoils) or through objects (pipes, engines) and it is the usual condition of airflow considered in engineering applications. Turbulent flow can be thought of as a continuous series of randomly orientated eddies of various sizes and intensity that are linked in a form of energy cascade. This energy cascade is the physical mechanism that dissipates the energy that the immersed object imparts to the flow (i.e. the fluid reaction to drag and lift). Hence, turbulent flow is unsteady and contains fluctuating eddies with a large range of sizes (or scales). Fluctuating eddies by themselves are a source of noise, the most familiar form being caused by airline jet engines. The addition of a close boundary, such as an airfoil, will amplify the noise generated by fluid turbulence.

Figure 1 is a diagram illustrating TE noise. On the left of the figure are some technologies where TE noise needs to be considered in their design. On the right of the figure, the major flow processes that occur over an airfoil placed in an otherwise uniform, steady and quiet fluid stream are shown. The flow encounters the leading edge of the airfoil and forms a boundary layer due to fluid shear that normally transitions to a turbulent state on the surface of the airfoil. Figure 1 illustrates the growth of this boundary layer over the airfoil surface and defines its thickness at the TE as δ. Turbulent eddies are formed within the boundary layer and it is the interaction of these eddies with the TE that generates broadband aerodynamic noise.

In acoustic terms, the edge presents itself as a sharp impedance discontinuity. This discontinuity scatters acoustic waves generated by fluid turbulence (considered to be quadrupoles) and creates an intensified radiated acoustic field [6]. When the dimensions of the airfoil are small compared with the radiated acoustic wavelength (chord = $C << \lambda$ = acoustic wavelength), then the fluctuating flow causes surface pressure fluctuations that are (effectively instantaneously) transmitted across the airfoil in the hydrodynamic near field. In this case, the radiated sound is of dipole character with strength proportional to the fluctuating total force amplitude. This type of noise amplitude scales with the sixth power of the Mach number (M^6).

When the airfoil dimensions are large compared with the radiated acoustic wavelength ($C >> \lambda$), the TE will diffract turbulence induced quadrupole noise. In this case, the intensified radiated noise is still of a multipole nature (sometimes known as a 3/2 pole) with an amplitude governed by the intensity and spatial distribution of the turbulent field. Diffracted turbulence scales with M^5, hence for a subsonic flow ($M < 1$) this noise is more intense than the dipole case described above. More detailed descriptions of TE noise generation processes can be found in Ref. [2] and theoretical descriptions of acoustic scattering and diffraction mechanisms can be found in Ref.[7].

The airfoil in Fig. 1 also includes TE bluntness of thickness h. The effect of bluntness is to create vortex shedding in the wake of the airfoil. This creates a stream of counter-rotating vortices with a higher span-wise (z-direction) coherency than the turbulent eddies in the turbulent boundary layer.

This results in tonal noise, sometimes of dipole nature if the wavelength is smaller than the chord. The diffraction of boundary layer turbulence, on the other hand, creates broadband noise up to high frequencies.

Figure 2 illustrates the general features of the noise spectrum created by these two sound generation mechanisms at the TE.

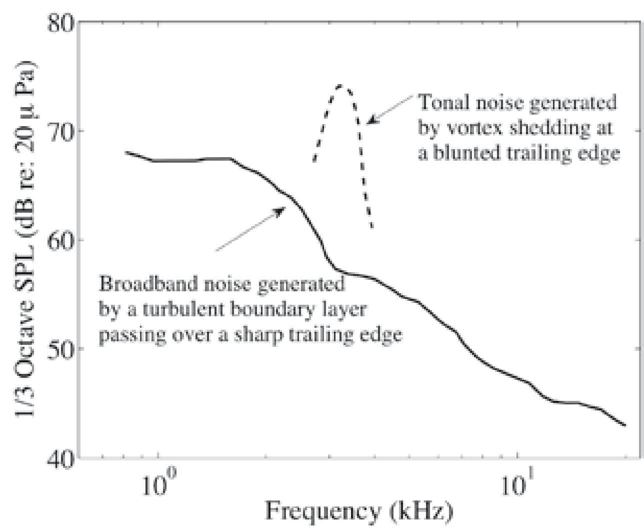

Figure 2. Illustration of flow induced TE noise spectrum. This figure was constructed using data from Ref. [5]. The broadband noise spectrum was measured for a NACA 0012 airfoil with a sharp trailing edge operating at a Reynolds number of 7.2×10^5 and a Mach number of 0.2. The tonal noise spectrum was measured for a NACA 0012 airfoil with trailing edge bluntness ($h/C = 0.06$) operating with a Reynolds number of 2.8×10^6 and a Mach number of 0.2.

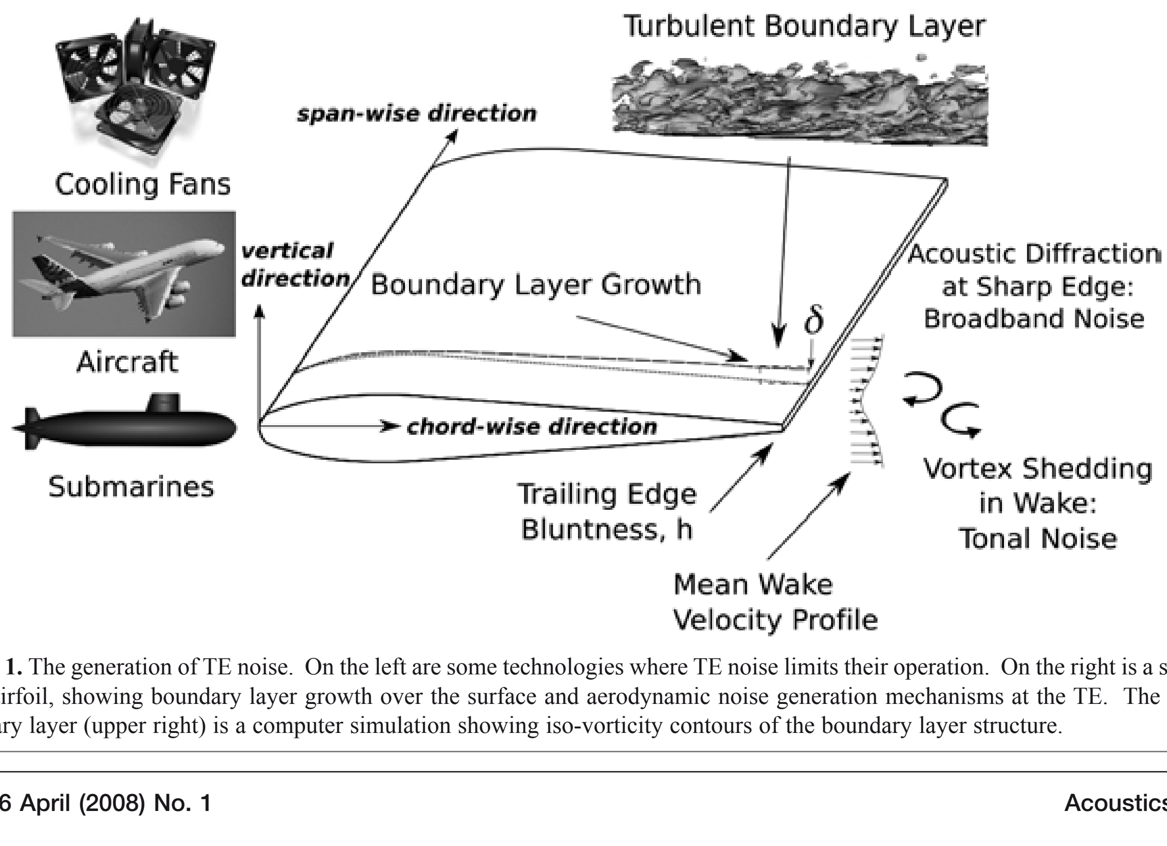

Figure 1. The generation of TE noise. On the left are some technologies where TE noise limits their operation. On the right is a schematic of an airfoil, showing boundary layer growth over the surface and aerodynamic noise generation mechanisms at the TE. The turbulent boundary layer (upper right) is a computer simulation showing iso-vorticity contours of the boundary layer structure.

3. THEORETICAL BACKGROUND

To illustrate the challenges involved in modelling and predicting TE noise, consider Lighthill's acoustic analogy [8]

$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \frac{\partial^2 \rho'}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \quad (1)$$

which expresses the wave equation for fluctuating density (ρ') with a source term proportional to Lighthill's stress tensor (T_{ij})

$$T_{ij} = \rho u_i u_j - \tau_{ij} + p' - c_0^2 \rho' \delta_{ij} \quad (2)$$

where u_i, is the velocity of the flow in the *i*-direction, τ_{ij} represents the viscous forces, p' is the fluctuating pressure and δ_{ij} is the Kronecker delta (see Ref. [9] for a complete derivation). What is interesting about this formulation is that no assumptions have been made during its derivation, which implies that all fluid flow can be described as an acoustic field. The final three terms are usually neglected when performing an aeroacoustic prediction. Hence, the source of noise is related to the fluid motion (first term), which is the Reynolds stress tensor, a familiar quantity to those involved in turbulent flow research.

What these methods tells us is if the turbulent flow about the TE were perfectly known, then calculating far field noise would be accurate and the design of quiet airfoils would be a trivial matter. However, this is not the case and describing TE turbulent flow remains a great scientific challenge. Therefore, the development and design of quiet airfoils is intricately linked to the development of turbulence simulation techniques.

4. TRAILING EDGE NOISE COMPUTATION

Figure 3 is a schematic 'road map' that shows the various methods of computing TE noise. Given the required inputs of airfoil geometry and flow condition (e.g. Mach number, Reynolds number, etc), different methods can be chosen in a left-to-right manner to arrive at an estimation of TE noise (the output).

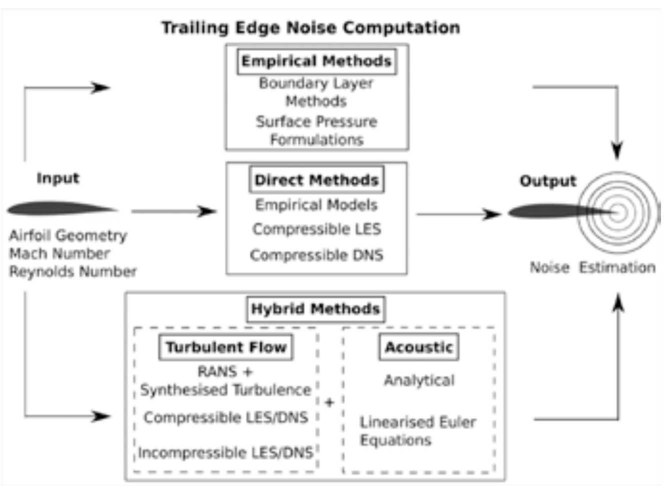

Figure 3. TE noise computation road map.

The techniques have been classified into three broad areas that have been termed as the empirical, direct and hybrid methods. The empirical methods were derived from anechoic wind tunnel results. In the direct method, an estimation of the noise can be made in a single computational step that calculates both turbulent flow and noise. The hybrid method assumes that the flow and noise are decoupled and can be calculated in two steps. An estimation of the turbulent flow field is obtained in the first step and the sound field is then computed using the turbulent flow field as the source in the second step. The various methods are discussed below.

4.1 Empirical Methods

4.1.1 Boundary Layer Methods

Approximately 25-30 years ago, engineers and scientists did not have the ability to perform complex computer simulations of turbulent flows. Therefore, they relied upon models derived from experimental measurements. Two well known empirical models have been developed by NASA and are based on boundary layer height at the TE and airfoil Reynolds number. The most straightforward was developed by Schinkler and Amiet [10] for helicopter rotors, which was subsequently used to good effect in Ref. [11] to predict the noise of wind turbine blades. This took the form of a scaling law prediction for 1/3 octave noise

$$\mathbf{SPL}_{1/3} = 10\log_{10}\left\{3.5U_\infty^5 D\frac{\delta s}{r^2}\left(\frac{S}{0.1}\right)^4\left[\left(\frac{S}{0.1}\right)^{1.5}+0.5\right]^{-4}\right\} \quad (3)$$

where U_∞ is the free-stream velocity, D is a user defined directivity function, s is the span, r is the distance to the observer and $S = f\delta/U_\infty$ is the Strouhal number. A more detailed empirical model was developed by Brooks, Pope and Marcolini [5], known as the BPM model, which incorporates more types of airfoil self-noise (i.e. bluntness, separation, etc). While more comprehensive, the BPM model can be easily programmed and quickly give an estimate of TE noise.

Hence, the simplest TE noise predictive scheme would consist of a method of computing the boundary layer thickness at the TE and substituting this into Eq. (3) or the BPM model. However, as these models are empirical, they are limited to the range of experimental parameters that was used to develop them. These models also have a limited ability to incorporate changes in the turbulence field induced by geometrical changes. Therefore, their applicability is restricted to common airfoil shapes that have no span-wise variation in geometry or other modification to the TE (e.g. brushes, serrations, etc).

4.1.2 Surface Pressure Formulations

An alternative to the empirical models based on boundary layer thickness are the formulations based on fluctuating surface pressure. The advantage of these methods is that they eliminate the need for estimates of fluctuating velocity about the TE. It does this by re-casting the problem in terms of fluctuating surface pressure and the diffraction of evanescent hydrodynamic waves at a knife-edge. At the time of the development of these models, there was much progress in surface pressure measurement techniques (e.g. Ref. [12]) and this method enabled the use of these empirical measurements or a modelled turbulent wall pressure spectrum to predict noise.

Using this method, the peak radiated sound spectrum can be estimated by [2]

$$\Phi_{p,\mathrm{rad}}\left(r,\omega\right)_{\mathrm{PEAK}} \approx \frac{1}{2\pi} M_c \frac{s\Lambda_3^2}{r^2} \phi_{pp}\left(x,k_3,\omega\right) \qquad (4)$$

where M_c is the average convective Mach number of turbulence past the TE (i.e. the velocity of the turbulent eddies, not the flow, divided by the speed of sound), Λ_3 is the span-wise turbulent length scale, ω is the radial frequency, ϕ_{pp} is the transverse surface pressure fluctuation spectrum, with a spatial Fourier decomposition across the span (into wavenumbers, k_3) and across time (into frequencies, $\omega = 2\pi f$). Note that this method is limited to turbulence fields that are both spatially and temporally homogeneous, a situation that may not occur for new low noise airfoil designs.

The key to an accurate TE noise prediction is to estimate the turbulence properties correctly. Good noise predictions were made by Brooks and Hodgson [12] using data obtained from simultaneous noise and surface pressure measurements. For cases where the exact surface pressure spectrum (i.e. the turbulent field) is not known, estimates are used [2] and predictions are poor at high frequencies. Recently, Ref. [13] has used a surface pressure formulation with a boundary layer numerical flow simulation to improve the estimate of the fluctuating surface pressure spectrum. While an improvement in predicting the overall shape of the noise spectrum has been made, noise predictions are still 10 dB below what is measured experimentally. This can be attributed to inaccuracies in the modelling of turbulent flow properties. Much better agreement between theory and experiment was obtained by Casper and Farassat [14] using their so-called 'Formulation 1-B' surface pressure formulation technique.

5. COMPUTATIONAL AEROACOUSTICS

Since the development of the empirical models summarised above, there has been a rapid advance in the ability to compute complex turbulent flow fields. This has been driven by enormous increases in computational power. This development has resulted in the emergence of computational aeroacoutsics (CAA) that uses computational fluid dynamics (CFD) solutions to calculate the properties of the noise sources and, in some cases, propagate acoustic disturbances to the far-field.

In this paper, CAA encompasses both direct and hybrid methods. In the direct method, a single simulation calculates the turbulent flow field and propagation of acoustic waves. This form of CAA is used for compressible turbulent jet noise [15] however; there are limited applications of the direct method to TE noise in the literature. Only two examples could be found at the time of writing. One is the numerical study of Ref. [16] where low Reynolds number flow was simulated over an infinitely thin, two-dimensional TE and compared with a theoretical model. The other is the high Reynolds number application of Ref. [17] that shows promising results but is not validated against theory or experiment. It is unlikely that the direct approach will be used routinely for high Reynolds number TE studies in the near future. This is because of the extreme computational cost required to simulate the fine turbulent structures in the boundary layer as well as resolve high frequency acoustic waves at large distances into the far field.

Hybrid methods represent the second main area of CAA and is the most popular technique for simulating TE noise. The basis of hybrid methods is to split the noise prediction into an aerodynamic/turbulence part to calculate the Reynolds stresses, then to use these as source terms in a second acoustic computation. Splitting the fluid dynamics and acoustic propagation is a sensible approach due to the very large separation of velocity and density scales. For example, the ratio of gas velocity at a listener's ear in the far-field to that at the source (i.e. the TE) is of the order of 10^{-3}-10^{-4}. Resolving such a wide variation in scales over a large computational domain is still too challenging for most desktop computers. This is because a large number of cells and costly, high-order discretisation methods are required. Excellent reviews of CAA numerical methods can be found in Refs. [18, 19, 20, 21] where these issues are discussed in more detail.

In the remainder of the paper, hybrid methods relating to TE noise estimation will be reviewed. Procedures that model the turbulent sources will be discussed first followed by techniques to predict far-field sound.

5.1 Prediction of Turbulent Flow

5.1.1 Synthesised Turbulence Methods

The most common method to simulate turbulent flow is to solve the Reynolds Averaged Navier Stokes (RANS) equations. This method produces a time-averaged flow field using a model to estimate the effects of turbulence. It produces mean turbulence quantities, such turbulent kinetic energy and dissipation rate, which can be used to calculate the integral scales of turbulence at every position within the flow. As the solution is time-averaged, spectral information about the Reynolds stresses is lost. It is not the intention to review RANS based CFD methods in this paper, therefore the reader is referred to Ref. [22] which provides one of the most thorough descriptions of RANS models and their implementation. What we are interested in here is how to use time averaged turbulence quantities to recreate a stochastic turbulence field.

Recently, methods have been devised to synthesise a turbulence field based on these time-averaged turbulence quantities [23, 24]. There has been a number of model turbulence spectrums developed over the years from experimental velocity correlations. Commonly used models are the Leipmann or Von Kármán spectra (see for example the appendix of Ref. [25]). These model spectra use the turbulence length scales calculated by the RANS model. Once the spectral information has been assumed, a deconvolution procedure is used to synthesise the transient velocity field at each point required by the noise prediction model. This information is subsequently used as the source terms in a separate acoustic prediction method.

5.1.2 Simulated Turbulence using Large Eddy Simulation

Large eddy simulation (LES) is more accurate than RANS for modelling a turbulent flow field however, until recently, LES has been limited to flows of academic interest due to its high computational cost. Projected performance increases in computational power and the rise of massively parallel computing, makes LES possible for engineering flows, such as turbulent TE noise.

The basis of LES is spatial filtering, rather than time-averaging, as is the case in RANS modelling. Spatial filtering has the consequence that turbulence scales larger than the grid size are directly resolved with no modelling assumptions. For turbulence scales smaller than the grid size, a special turbulence model is used, known as a sub-grid-scale (SGS) model. The model is transient, simulating the fluctuations directly above the grid scale, therefore requiring significantly more memory than RANS, which is steady state (as the turbulence is averaged over infinite time). As the grid is refined, LES will progressively resolve smaller turbulence scales, until eventually all turbulent scales are reproduced. In this case, the simulation is known as a Direct Numerical Simulation (DNS) and no SGS model is required. Current computers are not capable of performing a DNS of TE flows at realistic Reynolds numbers, hence LES will be the computational tool of choice for engineers and scientists wishing to calculate airfoil noise in the coming years. Reference [26] is an excellent textbook that describes the use of LES in acoustic calculation and can be used to learn more about these methods.

Recent attempts at coupling turbulence and TE noise calculations [27, 28, 29] reduce computational expense by modelling aspects of turbulence using an eddy viscosity model. Models of this type poorly predict noise levels at high frequencies [20]. It is important to correctly account for high frequency noise components as they are annoying to the human ear and are heavily weighted in aircraft and other noise regulations. Therefore, future research using LES for TE noise will need to develop new 'acoustical' SGS models to account for missing turbulence scales.

5.2 Prediction of Noise

5.2.1 Analytical Noise Prediction

Our attention now focuses on how to estimate noise from transient turbulent flow data (synthesised or simulated). Traditionally, analytical solutions are used. Ffowcs Willams and Hall [30] provided one of the first analytical solutions of Lighthill's acoustic analogy for turbulent diffraction about a semi-infinite half plane (knife-edged TE). This method derived an analytical Green's function for an idealised TE. Further theoretical development of the TE scattering and diffraction problem has been performed by Refs. [2, 6, 31, 32, 33].

The Ffowcs Williams Hall method has been successfully used by a number of researchers to calculate TE noise from incompressible LES simulation data [28, 29]. An incompressible LES assumes infinite sound speed in the fluid, hence no coupling is permitted between the fluid dynamics and acoustics. Reference [27] used a hybrid incompressible LES and Ffowcs-Williams Hall technique in a numerical optimisation routine to design a quiet airfoil. They found that by changing the shape of the TE, turbulent energy could be redistributed over smaller scales resulting in lower overall noise levels.

If a compressible LES can be performed, then analytical estimates of noise can theoretically be obtained using a free-space Green's function. This procedure uses the theory of Curle [34]. However, there appears to be no published study that couples a compressible LES with Curle's formulation. The Ffowcs William Hawkings [35] equation can be considered an extension of Curle's formulation that takes into account moving noise sources (such as a rotor blade) with respect to the listener. Reference [36] used the Ffowcs William Hawkings equation with a compressible LES to compute TE noise. While excellent results were obtained, they are yet to be validated. In fact, there are very few validated CAA TE noise results in the literature. In order to develop more accurate techniques, detailed comparison between computation and experiment is required.

5.2.2 Numerical Noise Prediction

Numerical methods can also be used to estimate TE noise. Here, the turbulent source terms from a CFD solution are used as a source for the propagation of acoustic disturbances. Recently, methods that solve the Linearised Euler Equations (LEE) have been developed. LEE methods were developed for jet flow [23] and have been in continuous development since [37, 38]. There has, however, been limited application to TE noise, with the work of Ewert and Schroder [39] being the only example. Ewert and Scroder developed a special variant of LEE known as the Acoustic Perturbation Equations (APE) where numerical errors were minimised.

LEE methods use the usual acoustic decomposition of flow variables into mean and perturbed parts. For example, a two-dimensional decomposition is

$$\begin{aligned} p &= \bar{p} + p' \\ u &= \bar{u} + u' \\ v &= \bar{v} + v' \\ \rho &= \bar{\rho} + \rho' \end{aligned} \tag{5}$$

where p is the pressure, u is the velocity in the x-direction, v is the velocity in the y-direction and ρ is the fluid density. The overbar denotes mean quantities and the prime denotes the perturbed part.

The linearised Euler equations are then found by substitution and linearisation of the Navier Stokes equations. e two-dimensional system of equations [37] is

$$\frac{\partial \mathrm{V}}{\partial t} + \frac{\partial \mathrm{E}}{\partial x} + \frac{\partial \mathrm{F}}{\partial y} + \mathrm{H} = \mathrm{S} \tag{6}$$

where the solution vector is

$$\mathbf{V} = \begin{bmatrix} p' \\ \bar{\rho}u' \\ \bar{\rho}v' \\ \rho' \end{bmatrix} \tag{7}$$

The flux terms are

$$\mathbf{E} = \begin{bmatrix} \bar{u}p' + \gamma\bar{p}u' \\ \bar{\rho}.\bar{u}u' + p' \\ \bar{\rho}.\bar{u}v' \\ \bar{\rho}u' + \rho'.\bar{u} \end{bmatrix}, \qquad \mathbf{F} = \begin{bmatrix} \bar{v}p' + \gamma\bar{p}v' \\ \bar{\rho}.\bar{v}u' \\ \bar{\rho}.\bar{v}v' + p' \\ \bar{\rho}v' + \rho'.\bar{v} \end{bmatrix} \tag{8}$$

where the ratio of specific heats for air is γ = 1.4. The vector **H** includes terms that depend on the derivative of mean source terms from a CFD solution.

$$\mathrm{H} = \begin{bmatrix} (1-\gamma)\left(u'\frac{\partial\bar{p}}{\partial x} - p'\frac{\partial\bar{u}}{\partial x} + v'\frac{\partial\bar{p}}{\partial y} - p'\frac{\partial\bar{v}}{\partial y}\right) \\ \left(\bar{\rho}u' + \rho'\bar{u}\right)\frac{\partial\bar{u}}{\partial x} + \left(\bar{\rho}v' + \rho'\bar{v}\right)\frac{\partial\bar{u}}{\partial y} \\ \left(\bar{\rho}u' + \rho'\bar{u}\right)\frac{\partial\bar{v}}{\partial x} + \left(\bar{\rho}v' + \rho'\bar{v}\right)\frac{\partial\bar{v}}{\partial y} \\ 0 \end{bmatrix} \tag{9}$$

The source terms are included in the following vector

$$\mathbf{S} = \begin{bmatrix} 0 \\ S_u - \bar{S}_u \\ S_v - \bar{S}_v \\ 0 \end{bmatrix} \tag{10}$$

$$S_u = -\frac{\partial\bar{\rho}u'v'}{\partial x}, \; S_v = -\frac{\partial\bar{\rho}v'u'}{\partial y}, \; \bar{S}_u = -\frac{\partial\overline{\rho uv}}{\partial x}, \; \bar{S}_v = -\frac{\partial\overline{\rho vu}}{\partial y} \tag{11}$$

Hence CFD determined noise sources (velocity fluctuations) are coupled to the acoustic computation through the assembly of the vector, **S**.

The use of LEE techniques is so far showing great promise, but there has been only one application to TE noise. In the single work that has applied LEE to TE noise [39], no comparisons have been made with experimental results.

Another numerical method for use in hybrid CAA schemes is the approach developed in Ref. [40]. Here, a variational formulation of Lighthill's acoustic analogy was derived and implemented using a finite element method. Large eddy simulation was used to determine the acoustic source terms. While the method was shown to work well, to date, there have been no comparisons made with experimental results.

CONCLUDING REMARKS

This paper has reviewed TE noise, which is one particular aspect of the overall phenomena known as airfoil self noise. It is a peculiar and academically interesting type of noise generating flow that also has wide practical application. A succinct overview of the latest work in this field has been presented, with a focus on airfoil TE noise prediction methods.

In order to design new, quiet airfoils, the computational techniques described above need further development. The largest issue that remains is experimental validation. In order to develop accurate and credible prediction methods, detailed experimental results are required. Surprisingly, there are few studies or datasets available that have detailed simultaneous TE turbulent flow and far field noise measurements. Future research must begin with turbulent flow and noise measurements about simple and complex geometry airfoils in a controlled environment such as an anechoic wind tunnel.

The modelling of the turbulent flow field needs improvement for better representation of turbulent scales. As LES will become the turbulent flow simulation technique of choice for engineers over the next 10-20 years, better SGS models are required to describe the finer scales of turbulence that affect high frequency noise components. There is a need to develop an 'acoustical' SGS model [20]. This, however, can only be done by thorough experimental validation and dedicated model development.

Numerical acoustic solvers, such as LEE solvers, have developed rapidly over the past few years and will play an increasingly important role in the design of quiet airfoils. However, critical aspects such as numerical stability and accuracy still need to be resolved through rigorous validation against analytical and experimental results.

The continued development of TE noise prediction methods brings about the possibility of numerically optimising TE shapes for quiet operation. This, in fact, has been attempted [27] at Stanford University using a hybrid LES/analytical noise prediction method. While only a preliminary study, the results were dramatic, showing a 10 dB reduction in sound power through the elimination of vortex shedding. Future research in this area will need to focus on improving model accuracy and efficiency as well as the development of more efficient optimisation routines.

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