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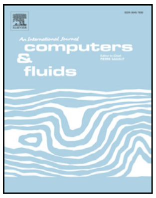

Using steady flow analysis for noise predictions

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ABSTRACT

Three different methods based on steady Reynolds-averaged Navier–Stokes (RANS) solutions are used to calculate the noise emitted from airfoils. Their results are compared to the ones obtained from experiments, a semi-empirical airfoil self-noise prediction code called NAFNoise developed by NREL, and large eddy simulations (LES). The three methods considered are a noise metric developed by Hosder et al. which can only predict overall sound pressure levels (OASPL) but no frequency spectra and two different statistical models developed by Doolan et al. and Remmler et al. The method by Doolan et al. employs a Green's function solution for airfoil trailing-edge far-field noise whereas the method by Remmler et al. predicts the pressure spectrum on the airfoil surface which is then used to compute the far-field sound by means of a hybrid noise prediction. All noise predictions were made at low speed and moderate Reynolds number similar to the environment of a small unmanned aerial system and involved different NACA airfoils as well as the SD 7003 airfoil.

1. Introduction and motivation

Airframe-generated noise is an important component of the total noise radiated from aircraft, especially during aircraft approach and landing, when engines operate at reduced thrust, and airframe components (such as high-lift devices) are in the deployed state. At these low Mach number and moderate Reynolds number conditions airfoil self noise is dominated by trailing edge (TE) noise [1] which has therefore been one of the main research areas of aeroacoustics for decades [2]. TE noise is generated by turbulent pressure fluctuations in the boundary layer, which when convected past the trailing edge encounter an impedance discontinuity and are scattered to the far-field as sound waves [3]. The TE noise of a conventional wing at high lift can be thought of as a lower bound value of the airframe noise on approach [4] and its value can also be used as a measure of merit in noise-reduction studies. There are many different approaches for the calculation of TE noise. Computational aeroacoustic (CAA) techniques can be used to directly calculate trailing edge noise by means of direct numerical simulations (DNS), large eddy simulations (LES), or possibly even unsteady Reynolds-averaged Navier–Stokes (URANS) computations. However, due to the high computational cost of any of these methods they are not very practical for airfoil design and it is much more common to solve just the steady RANS equations for aerodynamic calculations. Thus, it is highly desirable to couple noise prediction methods with steady RANS solutions. Unfortunately, noise is an inherently time-dependent phenomena and therefore a model of the acoustic source terms based on the Reynolds-averaged flow data needs to be employed [1].

Most theories on TE noise use Lighthill's acoustic analogy [5] and show that the noise intensity varies approximately with the fifth power of the freestream velocity and is also proportional to the TE length along the span and a characteristic length scale for turbulence [2,6]. Based on these observations, Hosder et al. [7] proposed a noise metric (NM) as a relative indicator of the clean-wing airframe noise which does not necessarily provide the magnitude of the actual noise signature but is suitable for design trade-off studies. Noise predictions which only compute the trends of the overall sound pressure levels (OASPL) but do not accurately capture the magnitude or frequency of peak noise run the risk of driving a vehicle design in the wrong direction. Nonetheless, OASPL may be adequate when comparing one component design to another, or if the noise spectrum is broadband without dominating narrow-band peaks.

If frequency spectra are desired mainly two different approaches based on statistical data provided by RANS have been developed; namely stochastic noise generation and radiation (SNGR) and statistical modeling of the turbulent sources. The SNGR approach generates a synthetic turbulent source field in the time domain based on RANS prescribed statistical information of the flow [8,9] but the computational storage and time requirements can be pretty large. The statistical modeling of the turbulent sources approach, on the other hand, is used to model only the surface pressure spectrum which in conjunction with a wave prop-

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agation program such as the Ffowcs Williams and Hawkings (FWH) approach [10] can be employed to estimate the far-field noise. Kraichnan [11] was the first to derive an expression for the pressure fluctuations on the wall as a function of the mean velocity profile and a two-point correlation of the velocity fluctuation components perpendicular to the wall. His work was extended by Lilley and Hodgson [12] and Lilley [13] to also be valid for boundary layers with a pressure gradient in the streamwise direction. Early application examples by Panton and Linebarger [14] used empirically determined analytical expressions for velocity fluctuations and turbulence length scale as inputs, however, with the readily available RANS data nowadays Lee et al. [15] showed that Kraichnan's approach can also be applied to more complex nonequilibrium-type boundary layers, such as the reattachment after a backward-facing step. For example, Rozenberg et al. [16] combined RANS simulations with semi-empirical wall-pressure spectra to compute the noise radiated by an automotive cooling fan and by an aircraft engine fan and Remmler et al. [17] applied a similar method to a Valeo controlled-diffusion airfoil.

A limitation of surface pressure models is the assumption of homogeneous turbulence in the spanwise and streamwise directions, a condition that is unlikely to hold in many TE configurations, particularly for adverse pressure gradients or spanwise modifications. A RANS-based statistical noise model (RSNM) has been proposed by Doolan et al. [1,18] which does not require the assumption of homogeneous turbulence. This method uses a semi-infinite hard-plane Green's function to calculate the acoustic far field directly using a statistical model of the turbulent sources in the boundary layer in the vicinity of the trailing edge. The method requires a model of the turbulent velocity cross-spectrum, which must accurately represent the frequency and phase distribution in the boundary layer [19,20].

The focus of this paper is to compare and validate the performance of three different methods for noise predictions using only steady RANS data which are the noise metric (NM) developed by Hosder et al. [7] and two different statistical models developed by Doolan et al. [1] and Remmler et al. [17]. It is very hard to find quality validation data in the literature and Tam and Ju [21] summarized the state of the art recently as follows "... it is fair to say that, at this time, no two experiments [for aerofoil tones] have the same result". The most cited study is the NASA Self noise modeling report by Brooks et al. [22] which is also going to be used here for validation purposes. More specifically, NAFNoise developed by NREL for the design of wind turbines [23] is used since it incorporates many of the noise models developed in the report by Brooks, Pope, and Marcolini (BPM) [22] with some additional modeling options for several airfoil noise generation mechanisms. The BPM modeling approach represents airfoil self noise as the combination of turbulent boundary layer trailing edge noise, separated flow noise, trailing edge bluntness noise, tip vortex formation noise, and laminar boundary layer vortex shedding noise. The code is only based on experimental measurements of the NACA 0012 section profiles. While the models generally reproduce the original experimental data, there is concern about applying the models at flow conditions outside of the original tests and to non-NACA 0012 airfoils [23]. The NAFNoise code includes the option to replace critical scaling parameters (e.g. boundary layer parameters) used in the BPM model with values computationally calculated using the aerodynamic modeling program XFOIL [24]. An additional turbulent boundary layer trailing edge noise modeling option (referred to as TNO) is also available in NAFNoise. The TNO model has been developed by Moriarty et al. [25] and is based on work by Blake [26] which uses the wave-number spectrum of unsteady surface pressures to estimate far-field noise.

The outline of the remainder of this paper is as follows. Sections 2–4 give the pertinent details of the three implemented noise prediction methods. Section 5 shows results for different validation cases as well as a camber noise study and Section 6 draws some conclusions.

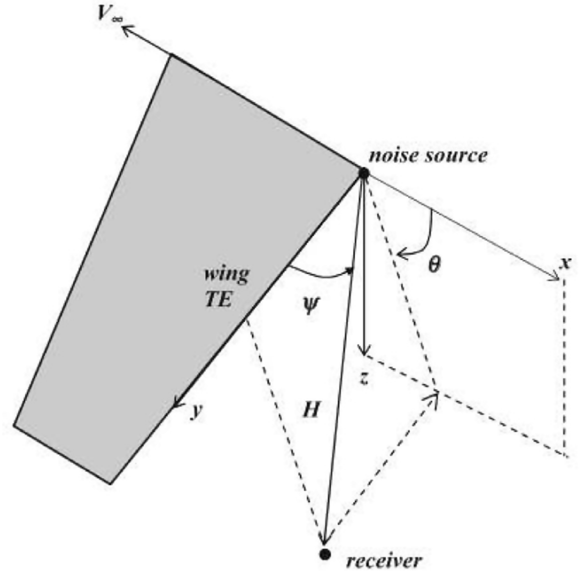

Fig. 1. Directivity angles definition (from Hosder et al. [7]). Here, the TE sweep angle β is zero.

2. RANS-based noise metric (NM)

The following gives a quick derivation of the noise metric proposed by Hosder et al. [7]. The starting point is the far-field noise intensity per unit volume, I, of acoustic TE sources which Goldstein [27] obtained by rewriting the Ffowcs Williams and Hall equation [28]:

$$I \approx \frac{\varrho_\infty}{2\pi^2 a_\infty^2 H^2}\omega_s u_s^4 \tag{1}$$

where ϱ_∞ is the freestream density, a_∞ is the freestream speed of sound, ω_s is the characteristic source frequency, u_s is the characteristic velocity scale for turbulence, and H is the distance to the far-field observer. Eq. (1) does not contain the dependency of the noise intensity on the directivity and the TE sweep angle, β. These dependencies can be included as follows [2]

$$I \approx \frac{\varrho_\infty}{2\pi^2 a_\infty^2}\omega_s u_s^4 \cos^3\beta \frac{D(\theta,\psi)}{H^2} \tag{2}$$

with the directivity term given by [28]

$$D(\theta,\psi) = 2\sin^2\left(\frac{\theta}{2}\right)\sin\psi \tag{3}$$

where θ is the polar directivity angle and ψ is the azimuthal directivity angle as defined in Fig. 1. Note that Doppler factors are not included in Eq. (2), because the focus of the current study is on flows with low Mach numbers where the relative velocity between the sources and the observer is small.

Using the Strouhal relation for turbulent flow [29], $\frac{\omega_s l_s}{u_s} \approx const.$, where l_s is a characteristic length scale for the turbulence, one can rewrite Eq. (2):

$$I \approx \frac{\varrho_\infty}{2\pi^2 a_\infty^2} u_s^5 l_s^{-1} \cos^3\beta \frac{D(\theta,\psi)}{H^2} \tag{4}$$

Accounting for the spanwise variation of the characteristic velocity and length scales, the TE sweep as well as the directivity angles

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