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Trailing edge noise prediction based on wall pressure spectrum models for NACA0012 airfoil

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ABSTRACT

This paper compares several approaches for the prediction of the noise emitted by a NACA0012 airfoil at 0° and 4° of angle of attack and a Reynolds number $Re = 1.5 \times 10^6$. Amiet's semi-analytical model for trailing-edge noise is combined with two-dimensional Reynolds-Averaged Navier-Stokes (RANS) computations. The wall-pressure spectrum, which constitutes the cornerstone of Amiet's model, is obtained by processing the boundary layer data extracted from the simulations. The specific contribution of the paper is a comparison of two families of prediction methods: semi-empirical wall-pressure models that are fitted to experimental databases, and statistical approaches based on the integration of the Poisson equation across the boundary layer profile. The semi-empirical models that were calibrated on airfoil databases provide better predictions with experiments, while the models based on flat-plate boundary layer data fail to reproduce the measured spectra. Considering the statistical approach, it was shown to predict the general spectral features, but with an overall under-prediction of about 3 dB. It can be concluded from this study that the statistical approach proves indeed more robust than semi-empirical models when the latter were not precisely calibrated for the flow under consideration. Further improvements of the statistical approach are suggested for future work.

1. Introduction

The increasing need for sustainable and clean energy resources is a strong incentive in the field of wind power. However, a main issue with the implementation of wind turbines is the acoustic disturbance they cause in their immediate environment (Bockstael et al., 2011; Waye and Öhrström, 2002; Schmidt and Klokker, 2014). Therefore, low-cost and precise noise prediction tools are needed in the process of wind turbine design and wind farm planning.

The predominant wind turbine noise production mechanism is associated with the turbulence that develops along the blade surface and scatters at the trailing edge as acoustic waves (Barone, 2011; Oerlemans et al., 2009). Trailing-edge noise prediction approaches can be distinguished along three categories; semi-empirical, direct and hybrid methods. The application of the semi-empirical models (Brooks et al., 1989) are limited since the models are calibrated against experimental data which can lead to poor prediction for other airfoil profiles and flow conditions (Moriarty and Migliore, 2003). The direct methods (Sanderg and Sandham, 2008; Gloerfelt and Le Garrec, 2009) provide accurate and reliable predictions and are applicable for industrial applications. However, when these high-fidelity methods are utilized as a design and optimization tool, they demand high computational cost (Herr et al., 2015). Hybrid methods offer an interesting compromise in terms of accuracy vs. CPU cost, by decoupling the flow and acoustic calculations (Redonnet, 2014). Hybrid methods usually consist of the following two steps: first, the unsteady flow field is computed in the region of the source term; secondly, an acoustic propagation method is used to compute the acoustic source radiation towards the far-field. In order to further reduce the computational cost, Reynolds-Averaged Navier-Stokes (RANS) simulations can be preferred over scale-resolved simulations to provide a source model. In that case, complementary stochastic methods are necessary to synthesize the missing unsteady information about the flow. The Stochastic Noise Generation and Radiation (SNGR) (Ewert, 2008; Herr et al., 2015) and Random Particle-Mesh (RPM) (Ewert, 2007) were developed to this end. Finally, purely statistical methods (not involving any stochastic reconstruction) offer the cheapest solution amongst the hybrid methods. The RANS-based Statistical Noise Model (RSNM) (Doolan et al., 2010) follows this path; the acoustic far field is computed using a semi-infinite half plane Green's function combined with a model for the turbulent velocity cross-spectrum in the vicinity of the

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trailing-edge. Alternatively, the wall-pressure based models compute the acoustic far field using a diffraction analogy technique (Chandiramani, 1974) or Amiet's theory (Amiet, 1975).

Amiet's theory requires the wall-pressure spectra information which can be obtained directly from Scale-Resolving Simulation (SRS). However, SRS computations require significant computational cost that is unappealing for industrial design and optimization tools. Kraichnan (1956) was the first to express the wall-pressure fluctuations for a flat plate based on the solution of the Poisson equation. The method expresses the pressure fluctuations in terms of the two-point correlation of the wall normal velocity fluctuations and the mean velocity profile. Following this approach the TNO model was developed by Parchen (1998), which is based on the turbulent boundary layer and the wall-pressure wavenumber frequency spectrum where Blake's equation (Blake, 1986) is used for the prediction of the wall-pressure wavenumber frequency spectrum. This model was observed to yield an under-prediction of the noise level compared to some experimental results (Kamruzzaman et al., 2011; Bertagnolio, 2008), even though it shows a correct behavior with respect to incoming velocity and angle of attack. Lilley and Hodgson (1960) developed an extended version of the Kraichnan (1956) method by considering the pressure gradient in the streamwise direction with empirically obtained inputs. Later, Panton and Linebarger (1974) expressed these inputs by empirically determined analytical expressions, yet this was insufficient to apply for more complex non-equilibrium flows. Lee et al. (2004) showed that the Kraichnan model is still applicable for more complex flows by obtaining the input parameters through RANS simulations of the reattachment after a backward-facing step. Lately, Remmler et al. (2010) applied this technique to zero and adverse pressure gradient flows. Besides simplified theoretical approaches, the development of the semi-empirical relationships has served to describe the pressure fluctuations beneath the boundary layer based on a theoretical basis. These models are derived by fitting the experimental wall-pressure spectra rescaled with the boundary layer variables. The model proposed by Schlinker and Amiet (1981) used the external variables to fit the experimental data obtained from Willmarth and Roos (1965). Later, Later, Howe (1998) reformulated the wall-pressure model proposed by Chase (1980) by re-scaling with the mixed boundary layer variables. The model exhibited better performance by capturing the ω^{-1} decay at high frequencies. However, this model does not take into account the Reynolds number effects where the overlap region increases at the intermediate frequencies. Moreover, this model does not capture ω^{-5} decay for the highest frequencies. Goody (2004) improved this model by adding a term in the denominator which satisfies the decay for high frequencies. He also added a non-dimensional variable that sets the overlap region depending on the Reynolds number. This model and earlier ones perform better for simple flows, however, they exhibit significant differences for Adverse Pressure Gradient (APG) and separated flows. Rozenberg et al. (2012) developed the Goody model for the APG flow by introducing two additional parameters which are Coles' wake, Π and Clauser's parameters, β_c. Catlett et al. (2015) extended the Goody model for APG flows by introducing non-dimensional parameters involving the Reynolds number and the Clauser's parameter. Kamruzzaman et al. (2015) proposed another model based on the Goody model by using airfoil measurement data. Hu and Herr (2016) claimed that using the shape factor, $H = \delta^*/\theta$ is more suitable for characterizing APG flows. Moreover, they suggested that the proper scaling for the spectrum should be the dynamic pressure as a better fitting is observed with their experimental data. Later, Lee and Villaescusa (2017) extended the Rozenberg model by modifying some of the terms to provide a better universal approach.

The models tend to focus on the accuracy of the wall-pressure spectrum predictions, however, there are few assessments of the far-field noise prediction. Furthermore, for the semi-empirical models, the determination of some of the required parameters is delicate, especially the boundary layer thickness in the presence of APG flows and the APG driven parameters such as Coles' wake parameter, Π and Clauser's equilibrium parameter, β_c .

Therefore, the purpose of this study is threefold:

- to investigate the sensitivity of the semi-empirical wall-pressure spectrum models on the boundary layer thickness determined by three different approaches and the APG driven parameters obtained by two different approaches;
- the comparison of the wall-pressure spectra obtained by six different semi-empirical models: Goody, Rozenberg, Catlett, Kamruzzaman, Hu & Herr and Lee as well as one statistical model, Panton & Linebarger;
- the comparison of the far-field noise prediction by Amiet's trailing edge model using the aforementioned wall-pressure spectrum models.

Section 2 of this paper focuses on Amiet's theory. Section 3 gives a brief description of the wall pressure models that have been investigated. The numerical simulation details are given in Section 4 and are validated against experimental wake profiles in Section 5. The wall-pressure spectrum models in Section 6 and far-field noise predictions in Section 7 are compared with the experimental data and the conclusion is drawn in Section 8.

2. Amiet's analytical model for trailing edge noise

Amiet's theory provides an analytical model to compute the broadband trailing-edge noise of an isolated airfoil. It is approximated as a flat plate with zero angle of attack embedded in a uniform flow. The main trailing-edge scattering is obtained by assuming that the chord is infinite in the upstream direction (Amiet, 1976). Later, a leading-edge back--scattering correction is performed by considering the finite length chord by Roger and Moreau (2005). The turbulent eddies convected by the mean flow at the trailing edge are assumed to be frozen. The far-field acoustic Power Spectral Density, PSD, (S_{pp}) for the trailing-edge for a large span airfoil and an observer located in the midspan plane at position, $x = (R, \theta, z = 0)$ for a given angular frequency (ω) can be written as:

$$S_{pp}(\mathbf{x},\omega) = \left(\frac{sin\theta}{2\pi R}\right)^2 (kc)^2 \frac{d}{2} \left| \mathscr{L}\right|^2 l_y(\omega)\phi_{pp}(\omega) \quad (1)$$

where c is the chord length, d is the span, l_y is the spanwise correlation length, ϕ_{pp} is the wall-pressure spectrum and $\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2$ is the aeroacoustic transfer function given by (Roger and Moreau, 2005) for super-critical, $\mathscr{L}_1$, and sub-critical, $\mathscr{L}_2$, gusts. It depends on geometrical parameters (chord and span) as well as on the pulsation ω. The spanwise correlation length is computed by the Corcos (1964) model as:

$$l_y(\omega) = \frac{b\ U_c}{\omega} \quad (2)$$

where U_c is the convection velocity, k_y is the spanwise wavenumber and a constant $b = 1.47$.

3. Wall-pressure spectrum models

3.1. The semi-empirical model

All the semi-empirical wall-pressure spectrum (WPS) models have the form of (Catlett et al., 2015; Hu and Herr, 2016; Lee and Villaescusa, 2017):

$$\frac{\phi_{pp}}{\phi^*} = \frac{a(\omega^*)^b}{[i(\omega^*)^c + d]^e + [fR^g\omega^*]^h} . \quad (3)$$

The shape of the spectra is modified through the parameters $a - h$ given in Eq. (3). The overall amplitude of the spectra is altered by a. The