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Towards a non-empirical trailing edge noise prediction model

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ABSTRACT

This paper extends previously published TNO-Blake model to predict airfoil broadband self-noise due to the interaction of a turbulent boundary layer with a sharp trailing edge. The main objectives of this paper are reduced the dependence on 'turning parameters'. The method presented herein combines an extension to Blake's model to predict the pressure fluctuation on the airfoil surface due to the turbulent boundary layer. Flat plate theory, with finite-chord effects included, is introduced to predict its subsequent radiation to the far field. The paper builds on recent advances in the prediction of the streamwise turbulent intensity profile to avoid the use of empirical relationships. Surface pressure spectra measurements are compared to predictions where agreement within 2 dB is obtained in the mid to high frequency range.

1. Introduction

Noise from an airfoil is generated when it interacts with a flow around it. Brooks et al. [1] have identified the following five self-noise mechanisms: the interaction between the turbulent boundary layer and the trailing edge, noise arising from the separated boundary layer, vortex shedding noise from the trailing edge due to the laminar boundary layer, noise arising from a blunt trailing edge, and the noise due to tip vortex formation. Provided that the airfoil is not stalled, the most significant source of broadband noise is due to the turbulent boundary layer convecting past the trailing edge.

The unsteady pressure developed beneath a turbulent boundary layer on the surface is referred to as the blocked pressure. It is twice the pressure that a nominally identical flow would produce if the wall was absent [2]. The solution for trailing edge noise studied in this paper is expressed in the wavenumber domain whereby the turbulent boundary layer wall-pressure is expressed in terms of its wavenumber-frequency spectrum. This consists of two distinctive regions: the acoustic region where wave components propagate at least as fast as the acoustic wave speed and therefore radiate efficiently to the far field, and the convective hydrodynamic region, where wave components convect slower than the acoustic wave speed and therefore do not radiate efficiently to the far field. Pressure fluctuations within the convective region are much greater than the acoustic region. Even though the radiation from this region is inefficient, it becomes the main source of noise upon interaction with surface roughness and/or other discontinuities (ribs, rivets, joints, etc.) at which convective energy is scattered into radiating components with supersonic wave speeds. This is mechanism associated with trailing edge self-noise.

When an airfoil is situated in a quiet (low-turbulence) flow it radiates broadband noise due to turbulent boundary layer vortical structures within the boundary layer on the airfoil surface interacting with the trailing edge. Ffowcs-Williams and

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Hall [3] were the first to recognize this significance of the trailing edge in the generation of self-noise. They derived an analytic expression for the far-field noise radiation that showed that the noise intensity depends on the 5th power of flow velocity, while noise emissions from a turbulent boundary layer, without a solid boundary, varies as the 8th power of flow velocity [4]. The efficiency by which the boundary layer pressure fluctuations radiate noise to the far field is therefore greatly amplified by being convected past the sharp edge.

The effect of a sharp trailing edge is to scatter hydrodynamic pressure fluctuations beneath the turbulent boundary layer of relatively short wavelength (U/f) that do not radiate to the far field, into acoustic waves that have much longer wavelength (c/f). Early predictions of the far-field broadband noise, for example by Chandiramani [5] and Chase [6,7], assume a semi-infinite rigid-plate and the boundary layer pressure fluctuations treated as evanescent wave components. These early studies make the assumption that the leading edge is sufficiently far upstream of the trailing edge for secondary leading edge interaction to be neglected. While this is a good approximation at sufficiently high frequency, at low frequency the effect of the finite chord, as well as secondary diffraction by the leading edge must be included. The effect of finite chord length was later introduced by Amiet [8,9], although the effect of secondary interaction by the leading edge was not included. Roger and Moreau [10] included this secondary effect, which they showed was important only at very low frequencies. An alternative approach that takes into consideration the effect of finite chord was proposed by Howe [11], which is consistent with the Amiet formulation in the low Mach number limit. The approaches to predicting trailing edge noise, such as by Roger and Moreau [10] and Lee and Cheong [12] for example, are formulated in the frequency domain where the turbulent statistics are described in terms of cross-spectra. Formulations of trailing edge noise in the time domain are less common, such as the work by Casper and Farassat [13] and Oberai et al. [14]. Despite these later developments the approximation of semi-infinite chord is still widely made, which introduces greatest error at low to moderate (non-dimensional) frequencies. In the low frequency limit, for example,the airfoil chord becomes acoustically compact and the radiation directivity is of classical lift dipole type, $\sin^2(\theta)$. As the frequency increases, main radiation lobes are introduced and tend towards the limiting pattern $\sin^2(\theta/2)$ of a semi-infinite half-plane.

Since the source of airfoil trailing edge self-noise is the turbulent boundary layer an accurate description of its statistical characteristics is required close to the trailing edge just before it convects over the edge. In the spectral solution of far-field noise investigated in this paper the boundary surface pressure spectrum is described in terms of its wavenumber-frequency spectrum at a position close to the trailing edge, but not too close such that the surface pressure is affected by back scattering of incident waves by the trailing edge. The prediction of the wall pressure fluctuations beneath a turbulent boundary layer on a flat plate was first investigated by Kraichnan [15] from solutions of the Poisson equation, which governs the relationship between the fluctuating pressure and velocity through the boundary layer. Smaller eddies situated close to the inner region of the boundary are generally responsible for high frequency pressure fluctuations on the surface while the large eddies situated in the outer region are responsible for the lower frequencies. A widely used model to describe the surface pressure fluctuations based on the solution to Poisson's equation has come to be referred to as the TNO-Blake model, which was developed from the work of Blake [16] and later extended by Parchen [17]. The original TNO-Blake model and most other extensions of this approach make the assumption of a semi-infinite half-plane which are therefore only valid in the high frequency limit [18,7].

The TNO-Blake model has been studied in detail by a number of authors but particularly by researchers at the Institute of Aerodynamics and Gas Dynamics (IAG) [19–21]. The boundary layer parameters required by the model were measured at the trailing edge of a number of large scale airfoil models in the closed-section of a laminar wind-tunnel at the IAG. The far-field noise was estimated from the coherent part of the velocity signal between two hot-wire sensors in order to reject background noise in the closed tunnel [22]. These measurements led to the conclusion that the original assumption of local isotropy in the turbulent boundary layer was incorrect. The TNO-Blake model was then further modified to include anisotropy in which the turbulence intensity and integral length-scale were allowed to be different in the three orthogonal directions [19]. Anisotropy was introduction through the introduction of ‘stretching’ coefficients in order to vary the ratios between streamwise and transverse mean square velocities and length-scales. Recent work of Bertagnolio et al. [23] has revisited the original model derivation by Blake [16] and discusses the effect of pressure gradient in the estimation of the surface pressure fluctuations and considers a frequency-dependent vertical correlation length. The introduction of anisotropy into the TNO-Blake model was shown to provide much improved predictions of the surface pressure and far-field noise spectra. However, in all this work the stretching coefficients were obtained by adjusting them to give best fit to the measured noise data. One of the innovations of the present work is that this empiricism is avoided by employing stretching coefficients consistent with classical values for a fully turbulent boundary layer.

In this paper we propose a number of modifications to the TNO-Blake model with the main objective of removing the dependence on tunable parameters. Predictions are compared against surface pressure and far-field noise spectra, measured in an open-jet anechoic wind tunnel facility at the University of the Southampton. The main innovations in the model are summarized herein: (i) the well defined ratios between mean square velocities and length-scale for a fully turbulent boundary layer are chosen thereby removing the requirement for empirical tuning parameters; (ii) the effect on noise radiation due to finite chord effects is incorporated by introduction of the Amiet [8] flat plate trailing edge theory; (iii) most significantly, the recent work by Alfredsson [24,25] in relating the mean square velocity boundary profiles to the mean velocity profiles is validated experimentally on an airfoil and incorporated into the model. The model is further assessed by comparison to integral boundary layer parameters predicted with empirical functions and XFOIL code [26] panel method.