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A Rapid Distortion Theory modified turbulence spectra for semi-analytical airfoil noise prediction

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ABSTRACT

This paper proposes an implementation of the Rapid Distortion Theory, for the prediction of the noise resulting from the interaction of an airfoil with incoming turbulence. In the framework of the semi-analytical modeling strategy known as Amiet's theory, this interaction mechanism is treated in a linearized form where the airfoil thickness, camber and angle of attack are assumed negligible, leading to a frozen turbulence description of the incident gust. Important semi-analytical developments have been proposed in the literature to improve the modeling of the gust–airfoil interaction accounting for parallel and skewed gusts, non-rectangular linearized airfoil shapes or blade tip effects. This work is rather focused on the investigation of the distortion of turbulence that occurs in the vicinity of the airfoil leading edge, compared with Rapid Distortion Theory, where main results are briefly reminded in this paper. The main contribution of this work is a detailed experimental investigation of the evolution of turbulent quantities relevant to noise production, performed in the close vicinity of the airfoil leading edge subjected to grid turbulence, by means of stereoscopic Particle Image Velocimetry measurements. The results indicate that the distortion effects are concentrated in a narrow region close to the stagnation point of the leading edge, with dimension of the order of its radius of curvature. Additionally, it is shown that the turbulence intensity grows significantly as the flow approaches the airfoil leading-edge. Based on those results, a modified turbulence spectrum is proposed to describe the incoming turbulence in Amiet's theory. The sound predictions show a significantly better match with acoustic measurements than using the original turbulence model.

1. Introduction

Aerodynamic noise has an important societal impact for air and ground transportation, home appliances and industrial machines. High-lift devices, fans, and propellers are commonly employed to provide air flow for ventilation and cooling, lift and propulsion. Given the importance and wide range of applications, the study of the airfoil noise production mechanisms is a fundamental step towards the development of quieter machines.

Aeroacoustic analogies indicate that at low Mach numbers and for compact source regions, airfoil noise generation can be related to pressure fluctuations over the blade surface [1], e.g. caused by the interaction of the airfoil with incoming

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List of symbols

b	airfoil semi-chord
c	airfoil chord ($c=2b$)
d	airfoil semi-span
s	airfoil span ($s=2d$)
U	upstream flow velocity
c_0	sound speed
M	flow Mach number; ($M=U/c_0$)
$\beta=\sqrt{1-M^2}$	compressibility factor
ω	perturbation angular frequency
$k=\omega/c_0$	wavenumber
$k_e=(\sqrt{\pi}/\Lambda_f)\Gamma(5/6)\Gamma(1/3)$	average wavenumber of the energy-containing eddies
$\overline{k}_x^*=k_x b/\beta^2$	dimensionless chordwise wavenumber
$k_x=\omega/U$	chordwise wavenumber
k_y	spanwise wavenumber
$\hat{l}(\mathbf{x}_0,\omega)$	elementary lift
$\mathbf{x}$	listener position
$\mathbf{x}_0$	source location on the airfoil surface
u'	velocity fluctuation root-mean-square
ρ_0	flow density

turbulence generated upstream of it and carried with the mean flow. In the model proposed by Amiet [2], this mechanism can be predicted along a two-step procedure: firstly, the aerodynamic response of the airfoil subjected to the incident gust is calculated by means of a linearized airfoil theory; secondly, the induced unsteady lift is propagated to the acoustic far field, accounting for mean flow and scattering effects where appropriate.

This procedure has benefited in the past years from significant developments, in order to obtain increasingly accurate calculations of the airfoil aerodynamic response [3–6], of the sound propagation [7–10], or including general acoustic installation effects [11,12]. This semi-analytical framework has permitted identifying some crucial parameters affecting sound production [7,13–15]. Among these input parameters, the incoming turbulent velocity spectrum is a key quantity directly affecting the accuracy of the sound prediction, while being possibly the most uncertain one. In the absence of better knowledge, canonical turbulence spectra (e.g. von Kármán, Liepmann) established for homogeneous and/or isotropic turbulence are usually assumed and scaled on the basis of statistical quantities that can be obtained from experiments or Reynolds Averaged Navier Stokes (RANS) simulations for example. Consistently with the linearized airfoil assumption, the rescaling data are generally obtained at a certain distance from the airfoil leading edge, and the turbulence is assumed to be convected without any subsequent alteration along the airfoil. However, a number of studies have highlighted that even for a relatively moderate airfoil thickness of the order of 10 percent, the incoming turbulence spectrum must be corrected to yield an acceptable agreement between predicted and measure sound spectra [3,7,13,15–17]. In these studies, the correction of the incoming spectrum is based on a theory derived by Hunt [18] and briefly detailed below, known as Rapid Distortion Theory (RDT), which accounts for the finite radius of curvature of the airfoil leading edge in the asymptotic limit of small turbulence scales compared with that radius. To the present authors knowledge, the alteration of the turbulence properties (e.g. correlation length and turbulence intensity) predicted by RDT were not confirmed experimentally for the case of a moderately thick airfoil, which constitutes the primary motivation of this work.

This paper presents stereoscopic Particle Image Velocimetry (stereo-PIV) measurements performed in the close vicinity of the leading edge of a NACA-0012 airfoil subjected to incoming grid turbulence. Of particular interest are the evolution of the spatial correlations, integral length scale and velocity root-mean-square (RMS) fluctuation. The structure of the paper is the following: in Section 2 the theoretical background pertaining to Amiet's theory, the effect of spanwise variations of the incoming flow and Rapid Distortion Theory are reminded. Section 4 describes the experimental campaign and results highlighting the turbulence distortion effects, and Section 5 illustrates the effect of using distorted incoming turbulence spectra as an input to the sound predictions. Conclusions are drawn in Section 6.

2. Theoretical background

2.1. Incoming turbulence noise

Following Amiet's formalism, we consider a linearized airfoil subjected to an incoming two-dimensional upwash velocity gust with amplitude w_0 and respective longitudinal and transverse wavenumbers k_x and k_y (Fig. 1). The aerodynamic gust produces an elementary unsteady force $\hat{l}(\mathbf{x}_0,\omega)$ which is modeled as an equivalent dipole perpendicular to the airfoil surface, at the coordinate $\mathbf{x}_0=(x_0,y_0,0)$ on the airfoil planform.

Curle's aeroacoustic analogy [1] relates the dipole strength and phase to the far-field sound at the listener coordinate $\mathbf{x}=(x,y,z)$:

$$p(\mathbf{x},\mathbf{x}_0,\omega)=\frac{\mathrm{i}k\hat{l}(\mathbf{x}_0,\omega)}{4\pi\sigma_s^2}\mathrm{e}^{-\mathrm{i}k\sigma_t}\left(1+\frac{1}{\mathrm{i}k\sigma_s}\right), \tag{1}$$

where $\sigma_s=\sqrt{(x-x_0)^2+\beta^2[(y-y_0)^2+(z-z_0)^2]}$ and $\sigma_t=[\sigma_s-M(x-x_0)]/\beta^2$ are distances between the source location and the listener position corrected for convective effects.

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