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Prediction of vortex-shedding noise from the blunt trailing edge of a flat plate

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ABSTRACT

A time-domain hybrid approach for aerodynamic noise prediction is developed based on a discrete vortex model (DVM) for the unsteady incompressible flow simulation and the acoustic perturbation equations (APE) for the acoustical field computation. The aim is to assess the applicability of the present DVM-APE method to the problems where sound is generated by the large-scale coherent flow structures. The hybrid DVM-APE approach is employed to predict the vortex-shedding noise from the blunt trailing edge of a flat plate. Simulations are implemented on flat plates with different thicknesses in a certain range of low Mach numbers, in order to identify the scaling dependence of the vortex-shedding noise on the freestream speed as well as the plate thickness. Acoustical directivity patterns at different Helmholtz numbers are presented, and agreements are achieved when compared with previous studies. A comparison of the sound pressure level spectrum between the present DVM-APE simulation and the published experimental results is also presented, showing good agreements for both the peak frequencies and the sound pressure levels.

1. Introduction

Trailing edge noise is the dominant contributor to airframe noise, fan noise, wind turbine noise, and other aerodynamic noise sources. In this context, prediction of trailing edge noise as well as understanding its mechanisms is of great concern for the design of modern low-noise aircrafts and wind turbines. It is known that the spectra associated with trailing edge noise can generally be divided into two kinds: broadband noise generated by turbulent boundary layer interacting with a sharp trailing edge at high Reynolds number and tonal or narrowband noise that may occur from either sharp or blunt trailing edges but due to different mechanisms, respectively. Previous experimental investigations have observed differently that an airfoil with a sharp trailing edge emits a single [1,2] or multiple tone(s) [3,4] in a uniform, moderate Reynolds number flow. The generation of tonal noise by sharp trailing edges has attracted increasing attention, but its underlying mechanism has not been concluded as a clear consensus and still remains to be an open issue [5,6]. However, as another origin of tonal noise, vortex-shedding noise due to the trailing edge bluntness [7] at low Mach number is a significant source of sound in many practical applications, of which the generation mechanism is more clearly understood. Large-scale vortex-shedding phenomenon appears in a separated flow region behind the blunt trailing edge, and the downstream convection of these shedding vortices leads to the formation of the Kármán vortex street in the wake. Then the vortex-shedding noise is

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generally attributed to the accompanied wall pressure fluctuations at surfaces near the trailing edge, which are caused by the unsteady circulations related to the shedding vortices in the wake. For this phenomenon, the challenging problem is how to predict the noise spectrum where there is a dominant peak. This paper focuses on the prediction of the vortex-shedding noise due to the bluntness of the trailing edge. The case chosen for investigation is the sound generation by vortex shedding from the blunt trailing edge of a thick flat plate.

Previous theoretical investigations [8–10] have revealed the mechanism of turbulence-edge interaction noise for a sharp edge and identified the predominant physical variables which affect this broadband trailing edge noise. These theories have been confirmed by the experimental results of Brooks and Hodgson [11]. However, the noise prediction models which focused on the narrowband noise produced by the vortex shedding from the blunt trailing edge were relatively rare. Related studies include the work of Blake [12], who proposed an expression that can be used to calculate vortex-shedding tones from the blunt trailing edge by means of the Powell-Howe acoustic analogy [13]. In this model [12], the Kármán vortex street was simplified as a two-dimensional, spatially periodic, distribution of vortices with periodically time-varying strengths, in order to relate the circulation of shedding vortices with the measured surface pressure. Roger et al. [14] developed a prediction model of vortex-shedding noise, in which a reversed Sears' problem was formulated to deduce the unsteady lift distribution and the far-field sound pressure was calculated by the acoustical formulation proposed by Paterson and Amiet [15]. Based on the transverse fluctuating velocity spectrum along with the wall-pressure spanwise coherence length from experimental data fitting, sound pressure level predicted by the model agreed well with the acoustical measurements [14]. In addition, the semi-empirical prediction models of trailing edge noise have been widely used in engineering applications [16]. The well-known NASA BPM airfoil noise prediction model [7] was developed on the basis of related aeroacoustics theories [8,17] as well as experimental database of NACA 0012 airfoils [7]. It dealt with five self-noise mechanisms including the turbulence-edge interaction noise and the vortex-shedding noise due to the trailing edge bluntness. However, when employed to predict the vortex-shedding noise in practical applications, the aforementioned prediction models more or less rely on either the information of the sound source or empirical parameters which both need to be acquired through measurements. Obviously, the application range of these models is limited by the experimental configurations. So not only tractable but also self-contained prediction methods should still be developed from the perspective of engineering applications.

With the development of computational fluid dynamics (CFD) and computational aeroacoustics (CAA), numerical simulations have been widely used to predict various fluid-structure interaction noise including the trailing edge noise. Wang and Moin [18] applied a hybrid method, which consisted of incompressible large eddy simulations (LES) for near-field flow simulation and the theory of Ffowcs Williams and Hall [8] for far-field sound prediction, to compute the flow and noise from an asymmetric, beveled trailing edge. This computation strategy was also employed by Manoha et al. [19] to predict the noise from the blunt trailing edge of a thick flat plate. Vortex-shedding noise was clearly identified from the narrow-band feature of the noise spectrum. The hybrid CFD-Acoustic Analogy or CFD-CAA approach was also employed by, for example, Singer et al. [20], Manoha et al. [21], and Wolf et al. [22], to study the generation and propagation of the trailing edge noise from the NACA 4-digit airfoil series. Besides hybrid methods, direct numerical simulations (DNS) [23,24] and direct noise computations (DNC) [25,26] were alternative ways to investigate trailing edge noise. Nevertheless, these methods are generally time-consuming and demand tremendous computational resources, especially for the unsteady flow field simulation.

This paper employs a hybrid approach to predict the vortex-shedding noise from the blunt trailing edge of a flat plate. Firstly, a proper simulation of the unsteady flow behind the trailing edge is fundamentally crucial for the prediction of the tonal noise. Previous experimental evidences [12] have shown that, at high Reynolds number, tonal noise due to vortex shedding from flat-plate trailing edge appears in the event that the bluntness parameter, which is defined as the ratio of the boundary layer thickness to the trailing edge thickness, is much smaller than unity. Recent experiments of Bilka et al. [27] also demonstrated similar phenomena with an asymmetric blunt trailing edge configuration. They found that in the case where the boundary layers were thinner compared with the trailing edge, narrowband vortex-shedding noise were observed, while when the boundary layers were thicker, acoustic spectra became broadband. Therefore, it is fair to say that the tonal noise from the blunt trailing edge hardly depends on the characteristics of the boundary layer. Such unsteady wake flow phenomena as large-scale coherent vortex shedding and downstream convection of vortical structures should be adequately represented. In this paper, a discrete vortex model (DVM) [28] of the flow behind the square trailing edge of a two-dimensional flat plate is adopted to simulate the near-field unsteady flow. This inviscid potential flow model can effectively capture the related flow features contributing to the tonal noise generation, such as vortex shedding and its subsequent convection. The near-field flow behind the blunt trailing edge is depicted by the distribution and the motion of discrete vortices. After that, acoustic perturbation equations (APE) [29] are numerically solved by CAA methods in time domain in order to obtain the radiated sound field. Acoustic perturbation equations were derived based on flow decomposition into acoustic and non-acoustic quantities through a filtering operation on the original source terms of linearized Euler equations. Only source terms that excite purely acoustic perturbations survive after the filtering process. There exists a set of APE with different construction of sound sources. The APE variant 4 with vortex-sound source terms are employed as the acoustic governing equations in the present study.

The paper is organized as follows. Section 2 presents the formulation details of the hybrid method based on DVM and APE. The simulation result of the unsteady, separated trailing edge flow is shown in Section 3. Section 4 presents the vortex-shedding noise prediction results including the radiated sound scaling law, far-field directivity patterns, and the prediction