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The control of aerodynamic sound due to boundary layer pressure gust scattering by trailing edge serrations

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ABSTRACT

A theoretical model is proposed in the current work to shed light on the noise-reduction mechanisms of trailing-edge serrations, which have been shown to suppress noise generated at the trailing edge due to the scattering of boundary layer pressure fluctuations. The current analytical model, which is developed by incorporating Fourier series expansions and the Wiener-Hopf method, can quickly predict noise reductions due to various types of trailing-edge serrations at low Mach numbers. The present model is validated by comparing its predictions with relevant published theoretical and experimental results. Moreover, from the Winer-Hopf analysis, an effective method based on Fourier series expansion is proposed to approximately evaluate the noise-reduction performance of different serrated geometries under various working conditions. The current work shows that trailing-edge serrations reduce noise by producing scattered waves with spanwise modes which could be evanescent, and explains why some serrated geometries are more effective than others in suppressing noise. The efficient noise prediction capability of the proposed model makes it very suitable to be used in the trailing-edge designs and evaluations of low-noise aircraft components such as wings and aero-engine fan, compressor and turbine cascades.

1. Introduction

Trailing-edge noise is a type of aerodynamic self-noise generated at the trailing edge due to the scattering of surface turbulent pressure fluctuations [1–5]. It is a significant source of both tonal and broadband noise from many aeronautical and underwater machines such as aircraft wings, propellers, aero-engine fan, compressor and turbine cascades, and wind turbines [6–10]. Hence the reduction of trailing-edge noise is important to many practical engineering applications and has already attracted considerable research attention [11–14]. Originally inspired by the silent flight of owls [15–17], the capability of trailing-edge serrations in noise attenuation has been demonstrated in many previous researches [1,18,19]. These past investigations, which include theoretical [19,20], experimental [18,21] and numerical studies [22], have broadly suggested that a serrated trailing edge attenuates aerodynamic noise through influencing both flow structures and noise scattering patterns. However, the true nature of the noise-attenuation mechanism is still not fully understood. For instance [1], attributed the noise-reduction effect of serrations to "an effective reduction in the spanwise length of the trailing edge", and [19] suggested "the destructive interference of the scattered surface pressure due to the presence of serrations" reduces noise. Furthermore, both [1] and [19] primarily

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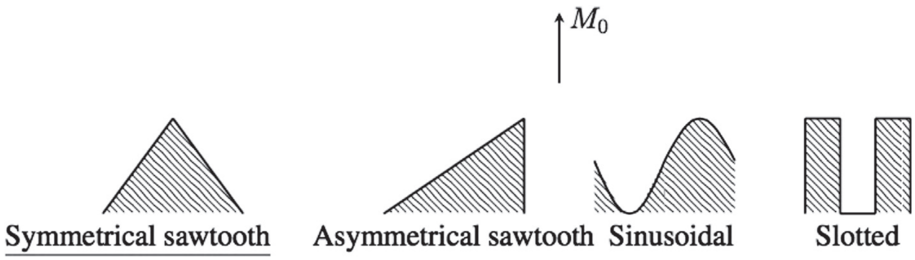

Fig. 1. Sketch of the serration geometries examined in this work. Many previous works refer the first and the second ones from the left as symmetrical sawtooth and asymmetrical sawtooth respectively. To avoid confusion, the first and the second geometries from the left are simply called as 'triangle' and 'sawtooth' respectively in the rest of this paper.

focused on sawtooth-shaped serrations and have provided enlightening physical insights, while the recent works [23,24] have experimentally considered various shaped trailing-edge serrations that call for theoretical explanations. The tailored Green's function from Howe [1] is valid for general shallow serrations; the difficulty is in analytically evaluating subsequent integrals. Likewise, the model by Lyu et al. [19] can also work for other serration geometry, the necessary changes are in the coupling matrices. Hence, we try to propose a new theoretical model in the current study to handle more arbitrary shapes of serrations (see Fig. 1) and to complement the overall understanding of related noise reduction mechanisms.

The current work adopts the concept proposed in recent researches [25,26] to take serrated trailing edges into account. More specifically, we use Fourier series to represent the geometrical layout of the periodic serrations, and establish a Wiener-Hopf based theoretical model to examine the scattered waves generated by the interaction between the pressure gust within the boundary layer and the serrated trailing edge. The Wiener-Hopf method is a powerful mathematical tool that has been used to generate closed-form analytical solutions for many classical scattering problems, such as diffraction from a rigid flat plate [27] and duct radiations [25,28–31]. For the flat plate case, Jone has developed a rigorous mathematical framework [32], which was then extended by Adamczyk for the investigation of cases with oblique gusts [33]. More recently [17], developed a mathematically beautiful Wiener-Hopf model for a poroelastic edge by combining an elastic plate model and the simplified two-dimensional (2D) Helmholtz equation. Their work deepens our understanding in the silent flight of owls. The current model is an extension to the one proposed in the recent work [26], which investigated the scattering due to incident external plane waves. In the present work, the previous matrix Wiener-Hopf model is further simplified to a series of scalar Wiener-Hopf models. Compared to previous theoretical models [1,19], the current one can handle different serrated geometries if the serrations can be represented by a Fourier series expansion. Recently [34], incorporated Fourier expansion into Schwarzschild techniques to perform noise predictions from sawtooth-shaped serrated leading edges. We believe that the current model can also be further modified to predict the noise due to the interaction between different shaped leading edges and incident vortical gusts.

The derivation of theoretical models is only possible by employing reasonable and justifiable simplifications and approximations. All existing theoretical trailing-edge noise prediction models (including the current one) employ the frozen turbulence assumption, i.e. turbulent eddies within the boundary layer convect past the trailing edge without changing their form. This important assumption enables the subsequent theoretical modelling either by using the Schwarzschild method [3] or by implementing an appropriate Green's function [35]. Although crucial in the derivations of many theoretical models, the validity of the frozen turbulence assumption is still arguable [12,36]. One recent experimental work [37] suggested that the discrepancy between the noise-reduction predictions by Howe's model and the corresponding experimental measurements is due to this assumption, and proposed that trailing-edge serrations attenuate noise by modifying the hydrodynamic field at the source location. Directly driven by these debates, the current model is developed differently compared to previous theoretical models. The use of the Wiener-Hopf method and Fourier series expansion in our model allows us to gain further physical understandings and insights from a new and different perspective.

The simplifications adopted in this work include a steady and uniform background mean flow, zero aerofoil thickness and camber, and the exclusion of the effects of downstream wakes, back-scattering from the leading edge, and the possible vortex shedding due to the coupling of the scattered sound field and the hydrodynamic field [38]. More practical configurations, such as non-flat plates [18,39], acoustic feedbacks [40], hydrodynamic effects [41] and non-zero angles of attack [42], could be more easily studied by computational and experimental methods. In addition, it has been known for many years that theoretical models usually overestimate the noise attenuation due to trailing-edge serrations compared to experimental observations. This could be caused by three possible factors: (1) some inherent physical features of flow and acoustics have been neglected by theoretical models, e.g., many experimental works have shown that trailing-edge serrations change turbulent flow at the aerodynamic sound source locations [21,37,43]; (2) during the experiment, other noise sources become relatively bigger and overwhelm the largely attenuated trailing-edge noise; and (3) a high background noise level (especially in the low-frequency range) of an ordinary test facility which masks the noise-reduction effect. Nevertheless, it will be shown later in this paper that the current proposed model can provide new and interesting physical insights, and will be very useful for parametric studies and design optimisations of trailing-edge serrations.

The remaining part of this paper is organised as follows. In section 2, the current problem is defined. Then, the current Wiener-Hopf based model for serrated trailing edges is derived in section 3. In addition to presenting the validation study