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On the aeroacoustic and flow structures developed on a flat plate with a serrated sawtooth trailing edge

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ABSTRACT

Results of an experimental study on turbulent flow over a flat plate with a serrated sawtooth trailing edge are presented in this paper. After tripping the boundary layer to become turbulent, the broadband noise sources at the sawtooth serrated trailing edge is studied by several experimental techniques. Broadband noise reduction by the serrated sawtooth trailing edge can be realistically achieved in the flat plate configuration. The variations of wall pressure power spectral density and the spanwise coherence (which relates to the spanwise correlation length) in a sawtooth trailing edge play a minor role in the mechanisms underpinning the reduction of self noise radiation. Conditional-averaging technique was applied in the boundary layer data where a pair of pressure-driven oblique vortical structures near the sawtooth side edges is identified. In the current flat plate configuration, the interaction between the vortical structures and the local turbulent boundary layer results in a redistribution of the momentum transport and turbulent shear stress near the sawtooth side edges as well as the sawtooth tip, thus affecting the efficiency of self noise radiation.

1. Introduction

Self noise emitted from the trailing edge of an airfoil blade represents a major environmental and operational issue in aviation, wind turbine and home appliance industries. There has been much interest recently in developing flow control methods aimed at reducing trailing edge self noise. For example, active flow control of wall-normal suction method was implemented at wind turbine blade to reduce trailing edge noise [1]. Another active flow control method for the suppression of trailing edge self noise is achieved by the Dielectric Barrier Discharge plasma actuators [2]. In this case, the induced air jet by the actuators can disrupt the growth of the boundary layer instabilities, thus resulting in the suppression of instability tonal noise.

In terms of airfoil self noise reduction by passive flow control, one of the most commonly used methods is inspired by the owl's wing. The unique feature of trailing edge serration is known to be quite effective in reducing both aerodynamic drag [3,4] and self noise radiation [5–11]. The serration has been studied in several forms: M-shaped [3,4], wavy [5] and sawtooth [6–11]. This paper focuses specifically on the sawtooth shape. A comprehensive experimental study by Gruber et al. [9] on many sawtooth geometries has established that significant noise reduction can be achieved if two conditions are fulfilled. The first is when the serration length is of the same order as the turbulent boundary layer thickness near the trailing edge.

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The second is when the serration angle is small, giving the appearance of a sharp sawtooth. These conditions generally agree well with the recommendation given by Howe [6].

In the case of a fully turbulent boundary layer, for example at high Reynolds numbers, or when tripping is applied, some of the turbulent energy in the boundary layer will be scattered into broadband noise at the trailing edge. The relationship between the far field acoustic pressure and the near field surface pressure near the trailing edge is made explicit in the classical work of Amiet [12] who derived a direct relationship between the power spectral density of the far field noise S_{pp} in terms of the spanwise correlation length l_y and the surface pressure spectrum S_{qq} near the trailing edge, and a radiation term $L(\omega)$, of the form $S_{pp}(\omega) \propto L(\omega) l_y(\omega) S_{qq}(\omega)$. This result predicts a reduction in the radiated broadband noise if the level of either l_y, S_{qq} and/or $L(\omega)$ is reduced. A sawtooth surface has the potential to modify one or more of the above three source terms, possibly leading to a reduction of the radiated noise.

The theoretical approach of Howe [6] assumes that as soon as obliqueness is introduced at the trailing edge, the coherences between the acoustic sources along the wetted edge will be reduced which ultimately result in a weaker noise radiation. The unsteady wall pressure spectrum in Howe's equations, however, is formulated by Chase's wall pressure model [13] for both the straight and serrated trailing edges. This implies that Howe disregards the hydrodynamic changes of the turbulent boundary layer over a serrated sawtooth trailing edge. The validity of this assumption has not been explicitly addressed.

In their investigation of the laminar instability tonal noise, Chong and Joseph [14] measured the boundary layer velocity power spectral density on the serrated sawtooth trailing edge at the pressure surface of a NACA0012 airfoil at 4.2° effective angle of attack. They observed that the boundary layer velocity spectrum actually exhibits increasingly turbulent characteristics towards the sawtooth tip. Moreau and Doolan [15] studied the near wake of a flat-plate with two kinds of serrated sawtooth trailing edges. They reported the modification of the wake characteristics in the serrated trailing edge and concluded that the upstream boundary layer must be modified by the serrated sawtooth trailing edge. A dissertation published by Pröbsting [16] provided some aerodynamic results on a nonflat plate type serrated trailing edge on a NACA0012 airfoil. By utilizing a tomographic PIV technique, a subset of coherent structures near the trailing edge was identified. Due to the blunt root of the serration, some longitudinal vortex shedding events have also been identified on the sawtooth surface, which apparently can produce tonal noise of a similar shedding frequency. Pröbsting [16] postulated that, through the vortex shedding event, the reduction in broadband noise by trailing edge serration could be related to the redistribution of energy within the turbulence spectrum.

Despite the recent publications by many authors on the subject, a consensus on the mechanism of broadband noise reduction by the serrated sawtooth trailing edge has not been reached. The main reason is that a more fundamental study on the boundary layer characteristics over a sawtooth surface remains scarce, especially from the experimental point of view. The expression from Amiet [12], which correlates the radiated acoustic pressure to the scattering of the hydrodynamic pressure waves near the trailing edge, provides an avenue for the investigation of the noise reduction mechanism by comparing the full wall pressure fields between a straight trailing edge and a serrated sawtooth trailing edge. However, it is very difficult to perform the above task when the serration is applied to an airfoil's trailing edge. This is because the physical size of the microphone will prohibit the wall pressure measurement at locations close to the side edges and tips of the sawtooth. In this work, a simple flat plate model was flush mounted to one side of the wind tunnel exit nozzle. The microphone can then be connected freely from the underside of the flat plate, which will allow wall pressure to be measured close to the trailing edges.

Self noise radiated by the above flat plate configuration for both the straight trailing edge and serrated sawtooth trailing edge was measured in an aeroacoustic facility. The noise results demonstrate that trailing edge broadband noise reduction can be realistically achieved by the serrated sawtooth trailing edge. This justifies the use of the flat plate model for the investigation of the noise reduction mechanism by serrated sawtooth trailing edge. The main parameters which are investigated in this paper include the unsteady wall pressure power spectral densities *(PSD)*, coherence functions and heat transfer characteristics across a full sawtooth surface. Boundary layer velocity measurements were performed to obtain the time-averaged velocity *PSD* and the Reynolds shear stresses. The boundary layer velocity signals were also conditionally-averaged to produce temporal variation of the momentum/turbulence properties across a sawtooth surface. An outlook section is provided to connect the observations in a flat plate to that of an airfoil, where both are subjected to serrated sawtooth trailing edges. It is hoped that the results presented in this paper can help to improve the understanding of the fundamental mechanism underpinning the reduction of self noise by a serrated sawtooth trailing edge, and also to provide an avenue for further development of other control techniques based on similar physical principles.

2. Experimental setup

2.1. Wind tunnels and test models

The aerodynamic measurements were conducted in an open jet wind tunnel which can achieve a maximum speed of about 35 m s^{-1}. Throughout the experiment, the freestream velocity was maintained at 30 m s^{-1}. The cross sectional area of the nozzle outlet is 50 mm × 150 mm. A flat plate extension of 150 mm × 295 mm was attached to one side of the nozzle lip, which is interchangeable with other flat plate models. Note that the background noise level produced by this open jet wind tunnel is excessive and cannot be used for any meaningful noise measurement.