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Experimental investigation of wavy leading edges on rod-aerofoil interaction noise

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ABSTRACT

Experimental studies are performed to investigate the effect of wavy leading edges on rod-aerofoil interaction noise in an open-jet anechoic wind tunnel. NACA 0012 aerofoils with straight and wavy leading edges (denoted by SLE and WLE, respectively) are embedded in the wake of a circular rod. The WLEs are in the form of sinusoidal profiles of amplitude, A, and wavelength, W. Parametric studies of the amplitude and wavelength characteristics are conducted to understand the effect of WLEs on noise reduction. It is observed that the sound power reduction level is sensitive to both the amplitude and wavelength of the WLEs. The WLE with the largest amplitude and smallest wavelength can achieve the most considerable noise reduction effect of up to 4 dB. The influences of rod diameter, d, and free-stream velocity, U_0, on the noise reduction effect of the WLEs are also investigated. In addition, a parametric study of the influence of separating rod-aerofoil distance on the acoustic radiation of the SLE case and on the sound power reduction level of the WLE cases is performed. It is found that a critical spacing exists where the acoustic radiation and noise reduction can be divided into two different “modes”.

1. Introduction

Aerofoil-turbulence interaction (ATI) noise is a significant contributor to the noise of aircraft engines, wind turbines, ventilation systems, high-lift devices, propellers, etc. ATI noise can be the dominant source when the incoming turbulence intensity is sufficiently high [1], which is very common, for example, at the leading edge (LE) of outlet guide vanes (OGV) in modern high bypass ratio turbofan engines. Therefore, a more in-depth study of ATI noise and its reduction are required to meet the increasingly stringent noise airworthiness regulations.

The wavy leading edge (WLE) was originally bio-inspired from Humpback whale flippers and has been identified as a lift-enhancing and drag-reducing treatment [2]. After this early morphological investigation, the WLE has become the subject of many studies so that their benefits in terms of improved aerodynamic and/or hydrodynamic performance can be explored. Most previous studies demonstrated that although the WLEs can delay stall occurrence, increase post-stall lift, decrease post-

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stall drag, and reduce laminar separation bubble, they may also degrade the pre-stall performance [3–15]. Miklosovic et al. investigated the effect of the WLE on aerofoil aerodynamic performance through wind tunnel measurements [3]. It was found that the addition of LE tubercles to a scale model of an idealized Humpback whale flipper could delay the stall angle by approximately 40%, while increasing lift and decreasing drag. Zhang et al. performed an experimental study of the control of aerofoil aerodynamics at a low Reynolds number within a range of attack angles using a sinusoidal LE protuberance [13]. They found that the wavy protuberances effectively suppressed aerofoil stall. The aerofoil aerodynamic performance was improved significantly in the post-stall region, leading to a maximum decrease of 20% in drag coefficient and a maximum increase of 25% and 39.2% in lift coefficient and lift-to-drag ratio, respectively. However, the aerodynamic performance was impaired to some extent in the pre-stall region. The protuberances may act in a similar way as low-profile vortex generators, which can induce streamwise vortices to control the boundary layer separation.

In addition to the aerodynamic aspects, WLEs have also been used to reduce both aerofoil self-noise and ATI noise in recent years. Laminar boundary layer-vortex shedding noise is one of the most important aerofoil self-noise mechanisms according to Brooks et al. [16]. Vortex shedding noise is essentially due to instabilities in the laminar boundary layer on the pressure/suction side of the aerofoil. These instabilities are in the form of Tollmien–Schlichting (T–S) waves and interact with the trailing edge of the aerofoil to generate acoustic waves that radiate upstream from the trailing edge and form an acoustic feedback loop system with the source of the instabilities, thus triggering a fluid-acoustic resonance effect that can radiate dominant narrowband acoustic tones. Many investigations have been conducted to explore the mechanism of the laminar boundary layer instability noise and its reduction [17–25]. Noise and performance tests were conducted on low-tip speed, axial flow fans by Longhouse [17] and wavy serrations were used to reduce vortex shedding noise. It was observed that serrations located at the LE, at the mid-chord, or near the trailing edge on the suction side could reduce the vortex shedding noise significantly. Hansen et al. [22] experimentally investigated the aeroacoustic effect of a wavy modification on the LE of a NACA 0021 aerofoil and found that the WLE with the largest amplitude and smallest wavelength achieved the most impressive tonal noise elimination effect. NACA 0012 aerofoils subjected to WLEs were designed by the present author to reduce the laminar boundary layer instability noise [25]. It was also found that the WLE with the largest amplitude and smallest wavelength provided the best tonal noise reduction. The mechanisms of tonal noise reduction were thought to be strongly related to the formation of counter-rotating streamwise vortices behind the troughs of the WLE, which can destroy the acoustic feedback loop.

The reduction of ATI noise with WLEs has been the subject of many experimental [26–33], numerical [34–38] and theoretical [39–41] studies. Narayanan et al. performed an experimental investigation into the use of the WLE as a means of reducing the broadband noise generated due to the interaction between the aerofoil's LE and the impinging turbulence [32]. Noise reduction effects were found to be insignificant at low frequencies but significant in the mid-frequency ranging from 500 Hz to 8 kHz. They also performed extensive parameter studies on the amplitude and wavelength of the WLE. In general, it was observed that the sound power reduction level was sensitive to the amplitude of the WLE but less sensitive to the wavelength. Similar conclusions have also been made by Lau et al., who performed high order accurate numerical simulations to investigate the effect of the WLE on aerofoil-gust interaction (AGI) noise [34]. Kim et al. performed full 3D inviscid Euler simulations for flat plate aerofoils with the SLE and WLE subjected to impinging synthetically generated turbulence [38]. Only the acoustic characteristics of flat plates with the WLE of different amplitudes were systematically investigated since the amplitude acted as the key parameter for enhancing the noise reduction effect. It was found that the sound power reduction level was almost proportional to the WLE amplitude. The noise reduction mechanisms were attributed to the source cut-off effect due to the geometric obliqueness and the phase interference effect along the LE of the WLE geometry.

Mathews and Peake [40] developed an analytical model for noise prediction associated with WLE serrations following Howe's approach, which was originally put forward to solve the trailing edge serration noise problem [42]. It was observed that noise reduction effect could be achieved using a serrated LE compared with the straight case, but the optimal noise-reduction choice of serration was difficult to predict for the different incoming eddies and turbulence. A generalized Amiet's model based on Schwarzschild's technique was derived to predict LE interaction noise with a saw-tooth LE [41]. The theoretical results showed an excellent agreement with experiments and this suggested that the model captured the essential physics of the serrated LEs.

The aforementioned discussions demonstrate unequivocally that the WLE is a potentially effective treatment for reducing broadband LE interaction noise. Most of the previous experimental studies, however, use approximately homogeneous and isotropic turbulence generated by turbulence grids as impinging disturbances, which can only produce turbulent broadband noise. The experimental configuration, in this paper, is that of an aerofoil embedded in the wake of a circular rod. The wake of the rod is composed of a periodic large-scale Karman vortex street and random small-scale turbulence. As a result, the aerofoil goes through a broadband disturbance that is dominated by a prominent shedding frequency, which is more like that observed in turbo-machinery applications. The current work will investigate the noise reduction potential of the WLE based on this rod-aerofoil tandem flow configuration in detail.

The organization of the paper is as follows. In Section 2, the experimental set-up and procedures are outlined. In Section 3, the effects of the WLE amplitude and wavelength on noise reduction are discussed. The effects of the inflow mean velocity and rod diameter on noise reduction are further demonstrated in Section 4. A parametric study of the influence of separating rod-aerofoil distance on the noise reduction level is presented in Section 5. Finally, some conclusions are drawn in Section 6.