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Leading- and trailing-edge noise reduction using serrations of new geometry

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Abstract

The leading-edge (LE) and trailing-edge (TE) noise due to the interaction of unsteady flow with the sharp edges of aerofoils are common in many engineering applications. One of the most widely used reduction methods is to use serrations, such as those of a sawtooth and a sinusoidal profile. The optimal serration geometry, however, remains largely unknown. We propose that a new ogee-shaped serration geometry can provide improved performance over conventional sawtooth serrations for leading- and trailing-edge noise reduction. In this study we carry out an experiment to investigate the noise reduction performance of the ogee-shaped serrations under various flow conditions. It is found that the new serration geometry provides an additional LE noise reduction compared to conventional sawtooth serrations under various flow conditions by up to approximately 8 dB. The additional noise reduction benefit starts to appear when $k_1 h > 3$ and becomes larger as the frequency increases until being hidden by the dominance of other noise source mechanisms. The new serrations only introduce more noise reduction but no noise increase at any other frequencies of interest. The use of LE serrations is found to be able to reduce the self noise. A preliminary TE noise test also sees additional noise benefit by using the ogee-shaped serrations.

Keywords: leading-edge noise, trailing-edge noise, serrations

1 INTRODUCTION

Leading-edge (LE) and trailing-edge (TE) noise, as two components of aerofoil noise [1, 6], are important noise sources in many applications. LE noise is generated when incoming turbulence impinges on the LE of aerofoils, leading to a strong interaction that causes the emission of LE noise. LE noise plays a crucial rule in many applications where noise becomes an issue. This is especially true in applications that more than one row of rotors and stators is installed, such as aero-engines, steam turbines and contra-rotating open rotors. In such systems, the wakes from the front row blades impinge on the downstream blades, resulting in a strong fluid-structure interaction as well as efficient noise radiation. In contrast, TE noise is generated when a turbulent boundary layer convects past the trailing edge of aerofoils and gets scattered into sound [15, 2]. TE noise is also important in many applications, especially when a highly turbulent boundary layer is common due to large Reynolds numbers, for example TE noise is important noise source for wind turbines.

Serrations have been proposed as one of the promising approaches to reduce LE noise [7, 13, 30, 19, 28]. Previous research on LE serrations includes experimental studies such as those by K. Hansen and Doolan [19] and Narayanan et al. [28], numerical investigations carried out by Lau et al. [21], Kim et al. [20] and Turner and Kim [33], and analytical examinations such as those by Lyu and Azarpeyvand [23], Ayton and Chaitanya [4], etc. Similarly, TE serrations have been widely used as an effective way of reducing the TE noise. Previous research includes a large bulk of experimental literature such as Dassen et al. [12], Chong et al. [11], Moreau and Doolan [27], Oerlemans et al. [29], Gruber et al. [14], Chong and Vathylakis [10] and Leon et al. [22], numerical simulations such as those by Jones and Sandberg [18], Sanjose et al. [31] and Velden et al. [34], and

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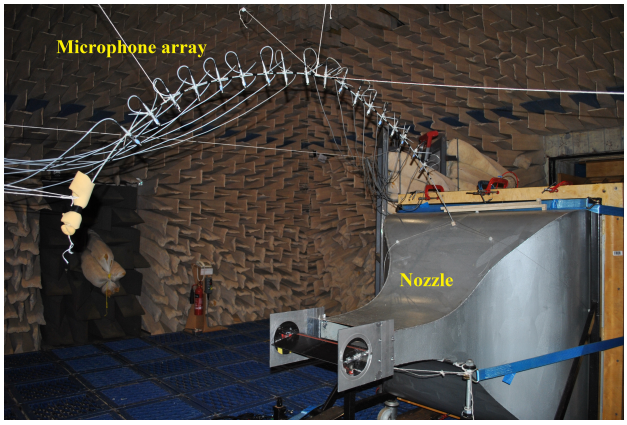
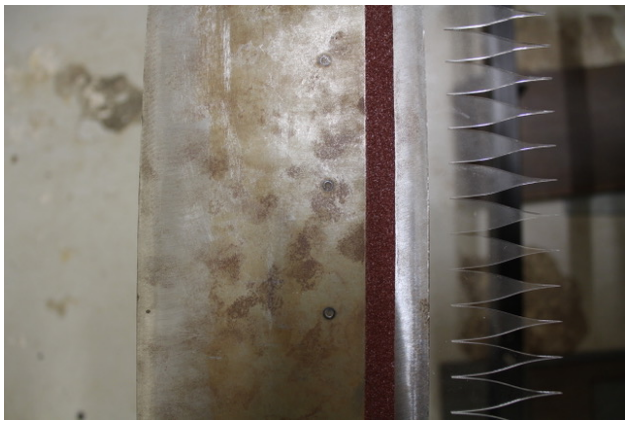


(a) The flat plate is placed near the exit of the wind tunnel and a microphone arc is suspended above the aerofoil to measure the far-field noise.



(b) The new ogee serration is inserted to the leading edge of flat plates. The sharpness at the tip and root can be varied by changing the parameter b in equation 1.

analytical studies such as Howe [16, 17], Azarpeyvand et al. [5], Sinayoko et al. [32], Lyu et al. [25, 24] and Ayton [3].

Although experiments and numerical simulations show that using serrations can reduce both LE and TE noise, it remains unclear how the serration geometry changes the noise reduction performance. Previous research has studied serrations of different geometry [19, 28, 8, 9]. These studies have shown that it is possible to achieve greater noise reduction via changing the serration geometries, but it is not clear what the optimal serrations geometry is. In a recent study of the authors [26], an asymptotic analysis was performed to show that in order to achieve greater noise reduction in the intermediate- and high-frequency range, the serration profile should not have stationary points and shaper slopes are favourable at the points where the profile function of the serrations is not smooth. An ogee-shaped geometry was proposed and shown both analytically and experimentally to be capable of reducing more LE noise. In this paper, we perform more extensive experimental tests, including a preliminary test on TE noise, to study the acoustic superiority of the new serration geometry in reducing LE and TE noise.

This paper is structured as follows. Section 2 briefly describes the experimental setup, while Section 3 presents noise spectra obtained for serrations of various sizes and geometries. The final section concludes this paper and lists some future work.

2 EXPERIMENTAL SETUP

The LE noise experiment is carried out in the aeroacoustic wind tunnel at the Institute of Sound and Vibration in Southampton. The facility has an anechoic chamber that measures 8 m $\times$ 8 m $\times$ 8 m and has a cut-off frequency around 80 Hz. A photograph of the rig is shown in figure 1a. In the experiment, the jet velocity U is varied between 20, 40, 60 and 80 m/s. The exit of the wind tunnel has a dimension of 150 mm $\times$ 450 mm, and a number of flat plates (a mean chord length 150 mm and span 450 mm) with different serration sizes and shapes are placed at 150 mm downstream of the wind tunnel exit. To prevent tonal noise generation due to the Tollmien-Schlichting waves convecting in the laminar boundary layer, the flow near the leading edge of the flat plate is tripped on both the pressure and suction sides to force transition to turbulence using a rough band of tape. Details about how the flat plates are connected with serrations can be found in Lyu et al. [26] and Narayanan et al. [28].

A baseline flat plate is included in the noise tests as reference. The ogee-shaped serrations used in this study,

as shown in figure 1b, are described by the shape function $F(\eta)$ as follows [26] (note the $\tan(\eta)$ function only represents one possible form for the ogee shape),

$$F(\eta) = \begin{cases} \dfrac{1}{\tan b/4}\tan(b\eta), & 0 \le \eta < 1/4, \\ \dfrac{1}{\tan b/4}\tan(b(-\eta+\dfrac{1}{2}), & 1/4 \le \eta < 3/4, \\ \dfrac{1}{\tan b/4}\tan(b(\eta-\dfrac{3}{4})), & 3/4 \le \eta \le 1, \end{cases} \tag{1}$$

where b is the parameter describing how sharp the serration is at the serration roots and tips. In the experiment, b takes the values of 0, π, 1.25π and 1.5π. When $b = 0$ the serration shape becomes the conventional sawtooth profile, and the slope at the root and tip becomes increasingly larger as b increases. The serration wavelength is denoted by λ, while h denotes the half root-to-tip amplitude. In the experiment, the value of λ varies from 5 mm to 15 mm, while h takes the value of 25 mm.

A microphone arc, as shown in figure 1a, is placed above the flat plate to measure the far-field noise at different angles in the mid-span plane. The arc consists of 11 1.27 cm condenser microphones (B&K type 4189) located at a radial distance of 1.2 m from the leading edge of the flat plate, spanning an observer angle from 40° to 140° measured relative to the downstream jet axis. Noise measurements are carried out for 10 s at a sample frequency of 50 kHz. The noise spectra are calculated with a window size of 1024 data points corresponding to a frequency resolution of 48.83 Hz and a BT product of approximately 500 , which is sufficient to ensure negligible variance in the spectral estimate at this frequency resolution. The noise spectra are presented in terms of the Sound Power Level (PWL) and Sound Pressure Level (SPL) using the procedure described by Narayanan et al. [28].

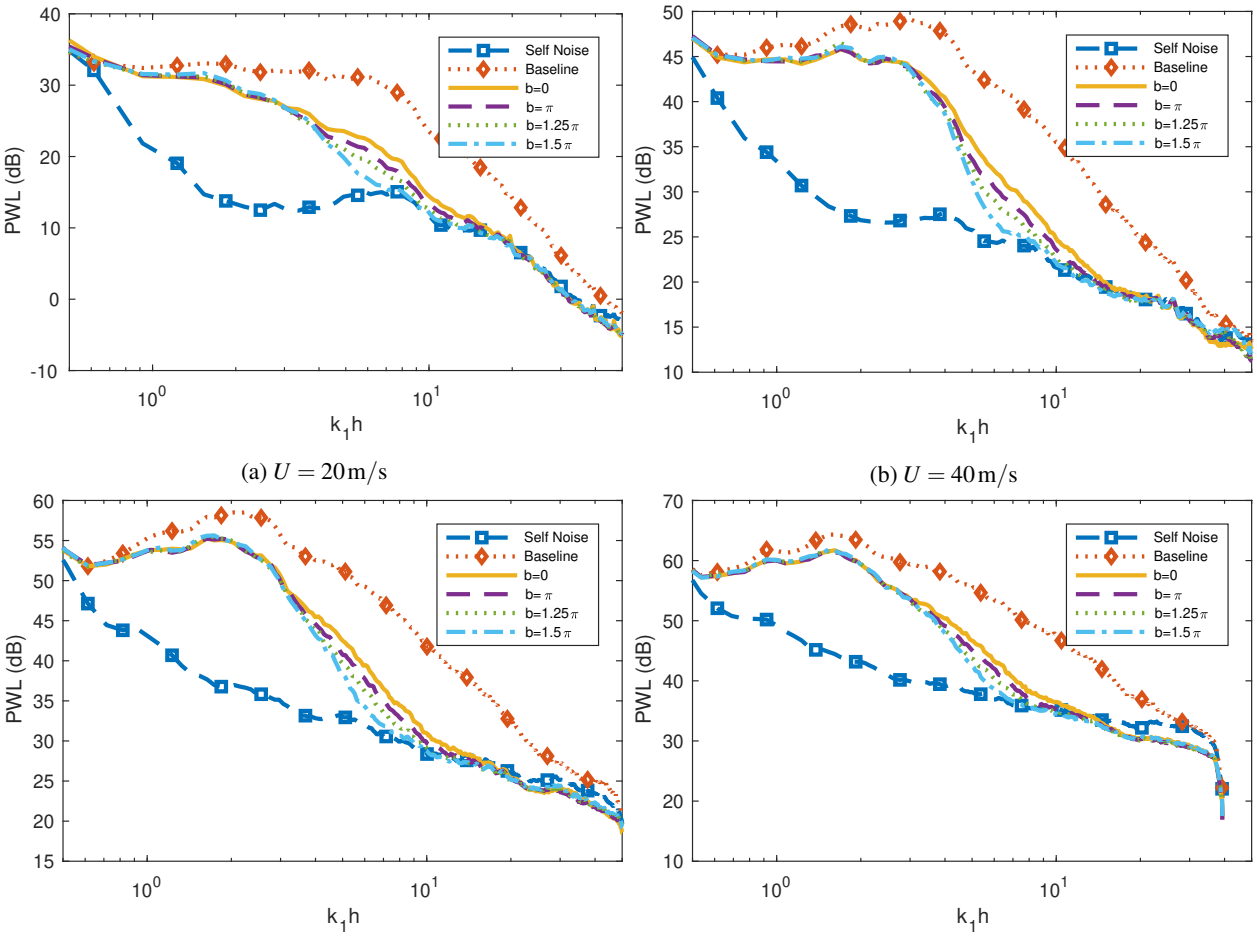
In the LE noise experiment, upstream turbulence is generated using a bi-planar rectangular grid of 630 mm × 690 mm. The grid is placed in the contraction section of the wind tunnel at 75 cm upstream the nozzle exit. The energy spectrum of the grid turbulence is known to be well modelled by a number of empirical formulae, such as the one based on the Von Kármàn spectrum [23, 26]. In this experiment, the turbulence intensity is around 2.5% and the streamwise integral length-scale is approximately 6 mm.

The TE noise experiment has a similar experimental setup as that for the LE noise measurements. Since this paper presents mainly the LE noise spectra, we omit a detail description, which will be introduced in detail in a following study.

3 RESULTS

In this section, we show the LE noise PWL spectra for various serrations. When these spectra are shown, the frequency is normalized as $k_1 h$, where $k_1 = \omega/U$ denoting the hydrodynamic convective wavenumber. For the results shown in this section, the self noise is measured using the baseline flat plate by removing the upstream turbulence grid, while the baseline spectra are measured by putting the grid back to the tunnel.

We first show the spectra for serrations of $\lambda = 10$ mm and $h = 25$ mm. These spectra can be found in figure 2. Figure 2a shows the spectra when $U = 20$ m/s. It is clear that because of this low speed the total sound level is quite low. It can be seen that the self noise is low for the frequencies $k_1 h < 10$ compared to the spectrum for the baseline LE noise. For frequencies satisfying $k_1 h > 10$ the self noise plays an important role in the total noise observed in the experiment and is only approximately 5 dB lower than the baseline spectrum. When the convectional sawtooth serration, i.e. $F(\eta)$ when $b = 0$, is used, a significant noise reduction is achieved for frequencies $k_1 h > 1$. Because of this reduction, the noise at frequencies $k_1 h > 10$ is virtually completely due to the contribution of self noise. As we increase the value of b, we can see increasingly more noise reduction



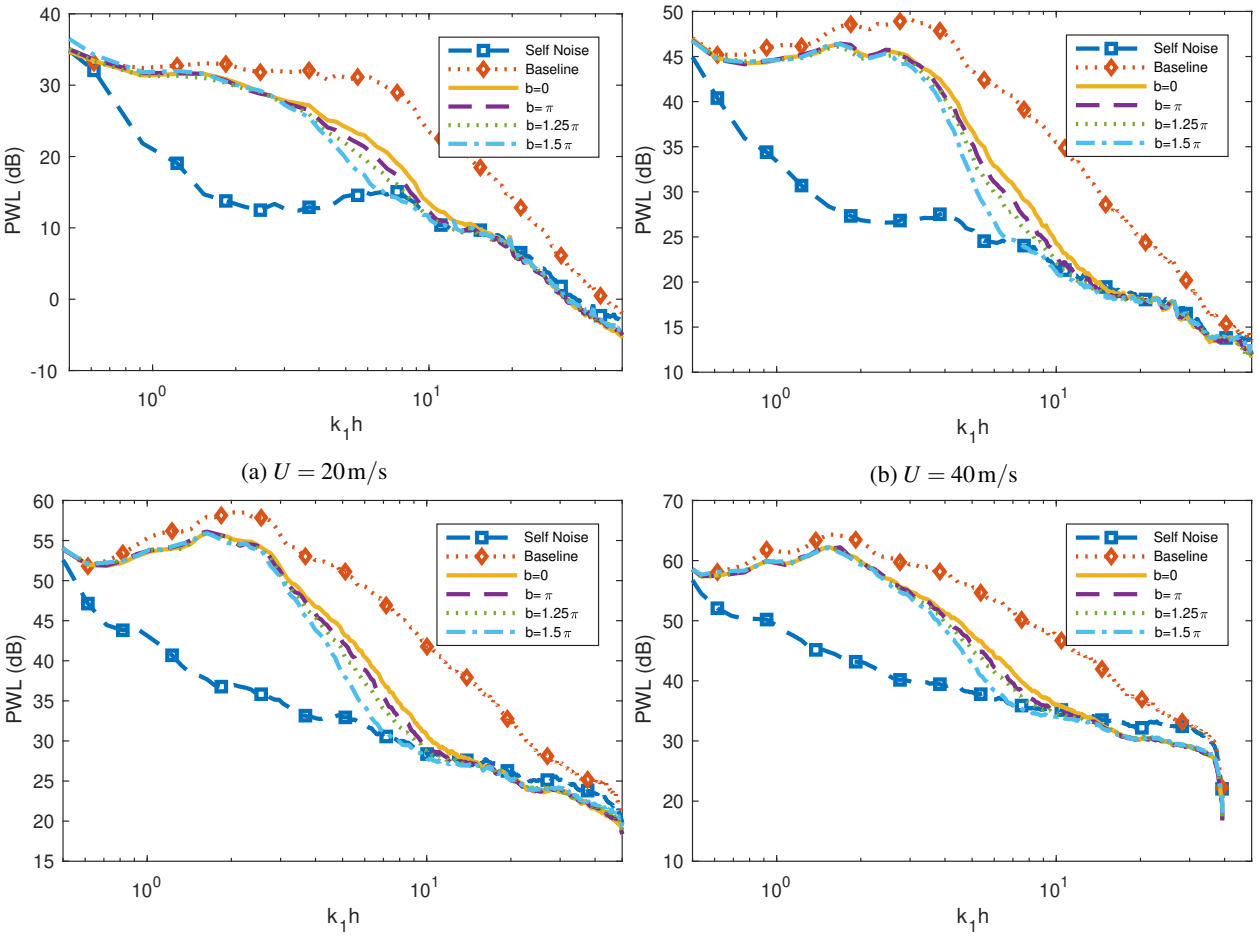
(a) $U = 20\,\mathrm{m/s}$ (b) $U = 40\,\mathrm{m/s}$

(c) $U = 60\,\mathrm{m/s}$ (d) $U = 80\,\mathrm{m/s}$

Figure 2. The noise PWL spectra for the serrations with $\lambda = 10\,\mathrm{mm}$ and $h = 25\,\mathrm{mm}$ but various values of b at various flow speeds.

for frequencies $3 < k_1 h < 10$. No more additional noise reduction is observed for frequencies $k_1 h > 10$, but this is due to the dominance of the self noise. Had the self noise been lower, we would have seen an extended frequency range over which additional noise reduction is achieved [26]. Although the advantageous frequency range is limited by the dominance of self noise at high frequencies, it is remarkable to see that there is virtually no sound increase at other frequencies. We have achieved an additional noise reduction simply by changing the serration shapes.

As we increase the velocity U, LE noise is louder, as can be seen from the PWL spectra shown in figures 2b to 2d. It seems that larger noise reduction benefit is achieved at $U = 40\,\mathrm{m/s}$ and $60\,\mathrm{m/s}$, while this advantage starts to drop slightly as U approaches to $80\,\mathrm{m/s}$. In each case, however, it is outstanding to see that no noise increase is observed at all frequencies by using the new serrations. Note it may seem surprising that the self noise is even larger than the total noise in figures 2c and 2d at high frequencies. This is because the self noise spectra are measured for the baseline flat plate. Using LE serrations in fact also reduces the self noise of flat plates, which explains the seemingly bizarre observation.



(a) $U = 20\,\mathrm{m/s}$ (b) $U = 40\,\mathrm{m/s}$

(c) $U = 60\,\mathrm{m/s}$ (d) $U = 80\,\mathrm{m/s}$

Figure 3. The noise PWL spectra for the serrations with $\lambda = 5\,\mathrm{mm}$ and $h = 25\,\mathrm{mm}$ but various values of b at various flow speeds.

Figure 3 shows the PWL spectra for narrower serrations, i.e. $\lambda = 5\,\mathrm{mm}$ and $h = 25\,\mathrm{mm}$. Examining figures 3a to 3d, we see that an even larger noise reduction benefit of up to 8 dB is achieved when a narrow serration is used, which is consistent to earlier analytical predictions [26]. The spectra in figures 3a to 3d are characteristically similar to figures 2a to 2d, but we note again that there is no noise increase at any frequencies due to the use of new serrations, and the limited advantageous band is due to the dominance of self noise. Since TE noise is typically prevalent at higher frequencies compared to LE noise, it expected that the additional benefit can carry over into higher frequencies when the new serrations are used to reduce TE noise.

4 CONCLUSIONS

An experimental study is performed in this paper to investigate the noise reduction performance of ogee-shaped serrations under various flow conditions. The ogee shape is described using a $\tan(\eta)$ function with a parameter b specifying the sharpness at its roots and tips. Moreover, the serrations wavelength is also varied. The flow velocity U is varied between $U = 20\,\mathrm{m/s}$, $40\,\mathrm{m/s}$, $60\,\mathrm{m/s}$ and $80\,\mathrm{m/s}$.

It is found that the new serration shape provides an additional LE noise reduction compared to conventional sawtooth serrations by up to approximately 8 dB. This additional noise reduction is slightly more pronounced when $U = 40\,\mathrm{m/s}$ and $60\,\mathrm{m/s}$. The additional LE noise reduction benefit starts to appear when $k_1 h > 3$ and becomes larger as the frequency increases until being hidden by other noise source mechanisms. The new serrations introduce only more noise reduction but no noise increase at any other frequencies of interest. The use of LE serrations can also reduce the self noise. A preliminary TE noise test also sees additional noise benefit by using the ogee-shaped serrations. A more extensive test campaign using the new serrations is ongoing and the results from these tests will be reported in our future work.

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