Nature-inspired aerofoil modification for leading edge interaction noise reductions

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ABSTRACT

This paper presents the results of an experimental investigation of the effect of add-on type leading edge serrations on the aeroacoustic performance of a symmetrical NACA0008 aerofoil. The focus is on the turbulence-leading edge interaction noise. Tests have been conducted in an aeroacoustic open jet wind tunnel. Several leading edge sawtooth serrations, generally those having larger amplitudes, have shown the ability to reduce broadband noise levels as much as 10 dB at certain frequency bands. However, serration designs with smaller amplitude have shown noticeable levels of noise increase at high frequency. Application of the bio-inspired curved serration geometry in most cases produces no significant difference when compared with the non-curved serration designs, although in certain cases further reduction in noise level at high frequency region can be observed. At increasing angles of attack, the effectiveness of the sawtooth serrations deteriorates significantly. At the largest angle of attack, the level of broadband noise reduction is significantly lowered, and at the same time noise increase at high frequency (up to 10 dB with a large frequency bandwidth) is present. Overall, the add-on type leading edge serration concept still demonstrates considerable interaction broadband noise reduction capabilities if the right serration amplitudes and wavelengths are chosen.

Keywords: Interaction noise, leading edge I-INCE Classification of Subjects Number(s): 21.6.5

1. INTRODUCTION

Recently, it has been shown that industrial impact to the environment is becoming an increasingly sensitive topic. The aeronautical industry is a substantial contributor to pollution levels on a global scale. However, aircraft engine manufacturers are constantly developing advanced and more efficient powerplants that produce smaller carbon footprints. Aircraft noise issue is also gaining significant attention in terms of their impact on communities that surround larger airports. This is mainly attributed to the expanding aircraft traffic and this problem is gaining momentum. The UK Department for Transport forecasts that the current national passenger traffic of ~254 million is expected to exceed 335 million by 2030. Such forecasts therefore call for regulations to be implemented by the airports or local authorities as a result of related regional initiatives such as ACARE Flightpath 2050. This European Commission backed programme sets goals to achieve 65% reduction in commercial aviation noise emissions by 2050, relative to year 2000.

The renewable energy industry could be another major area that actively seeking the latest noise reduction technology with advanced wind turbine blades. This is especially important since large expansion of wind farms as a sustainable energy source in recent years has induced large noise levels that the surrounding communities are exposed to. This, in turn, has been making the wind farm expansion an increasingly costly and complex process with the increasing need to construct such farms in less populated areas.

One of the dominant noise sources pertaining to the above industries is related to the leading edge-turbulence interaction noise. It has been shown in previous researches that leading edge noise is normally confined to lower frequencies and is thus related to larger freestream turbulent structures that

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are responsible for the noise generation, where these structures are convected downstream by the main flow. These turbulence structures interact with the leading edge of an aerofoil and are stretched around it, causing pressure fluctuations on the suction and pressure sides of the aerofoil, as well as amplifying the unsteady lift, before converting to the far field noise radiation (1).

In a joint experimental-numerical efforts by Clair et al. (2) on the NACA 65-(12)10 aerofoil, the serrated leading edge is found to achieve noise reduction between 3–4 dB. Narayanan et al. (3) assess the effects of a serrated leading edge on the turbulence–leading edge interaction noise for a flat plate, as well as a NACA 65-(12)10 aerofoil. A near isotropic turbulence was produced using mesh grid inside the nozzle. They demonstrated significant broadband noise reduction of 9 dB by flat plate and 7 dB by aerofoil configurations, respectively, using the largest serration amplitude. They suggested that the level of broadband noise reduction is a strong function of the serration amplitude, and is less sensitive to the serration wavelength. A recent inviscid numerical study by Kim et al. (4) exhibited a de-correlation of the surface pressure fluctuation and the far field noise on a serrated leading edge. In particular, the noise source at the mid-region of the oblique edge becomes ineffective across the mid to high frequency range. Another noise reduction mechanism is attributed to the phase interference and destruction effect between the serration peak and the mid-region of the oblique edge.

Fig. 1 Leading edge serrations on a wing of barn owl (3).

So far, the leading edge device for the reduction of interaction broadband noise is almost exclusively formed by the cut-in approach, i.e. the serration pattern is cut into the main body of the aerofoil. The manufacturing complexity is clearly the downside of the cut-in approach. The next step is to investigate whether flat-plate add-on type serration, which has clear technological advantage owing to their relative simplicity and ability to apply it to any aerofoil without the need to modify its actual geometry, can produce the same level of broadband noise reduction. This add-on device has the potential to find its way to application in propulsive machinery, turbofan engine fan blades and wind turbine. A novel design, central to this paper, has been inspired by ornithologists. It has been suggested that owls have unique wing morphology, i.e. the leading edge of an owl's wing exhibits comb-like curved serrations (see Fig. 1). Some researches carried out on owl's silent flight (mainly measurements of mid-flight noise emissions) have led to postulations that these serrations could be partially responsible for the unique in-flight noise reduction capability of an owl. As pointed out by Kim et al. (4), the main contributor to interaction noise radiation for a serrated leading edge is at the trough region. The curved serration found in the owl wing thus can shield the incoming turbulence structures, potentially further reduce the interaction noise level.

2. EXPERIMENTAL SETUP

2.1 Wind Tunnel Facility

Free field measurements of the aerofoil noise were conducted in the aeroacoustic open jet wind tunnel at Brunel University London, which is situated in a 4 m x 5 m x 3.4 m anechoic chamber. As shown in Fig. 2, the nozzle exit is rectangular with dimensions of 0.10 m (height) x 0.30 m (width). This wind tunnel can achieve a turbulence intensity of between 0.1–0.2% and a maximum jet velocity of about 80 ms^{-1}. The background noise of the wind tunnel facility is well below the self noise of the quietest airfoil across the whole range of velocity (6). The range of jet speeds under investigation was between 20 and 60 ms^{-1}, corresponding to Reynolds numbers based on C of 2 x 10^5 and 6 x 10^5 respectively. The aerofoil was held by side plates and attached flushed to the nozzle lips. Unless otherwise stated, the aerofoil is kept at angle of attack, $\alpha = 0^o$.

To generate large scale turbulence structure in the freestream, a bi-planar orthogonal square grid was placed inside the nozzle. The mesh length is 75 mm and the grid diameter is 15 mm. Hot-wire measurement of the freestream turbulence intensity and eddy length scale at location near the location of the aerofoil leading edge (but without the presence of the aerofoil) are 3.7% and 6.5 mm,

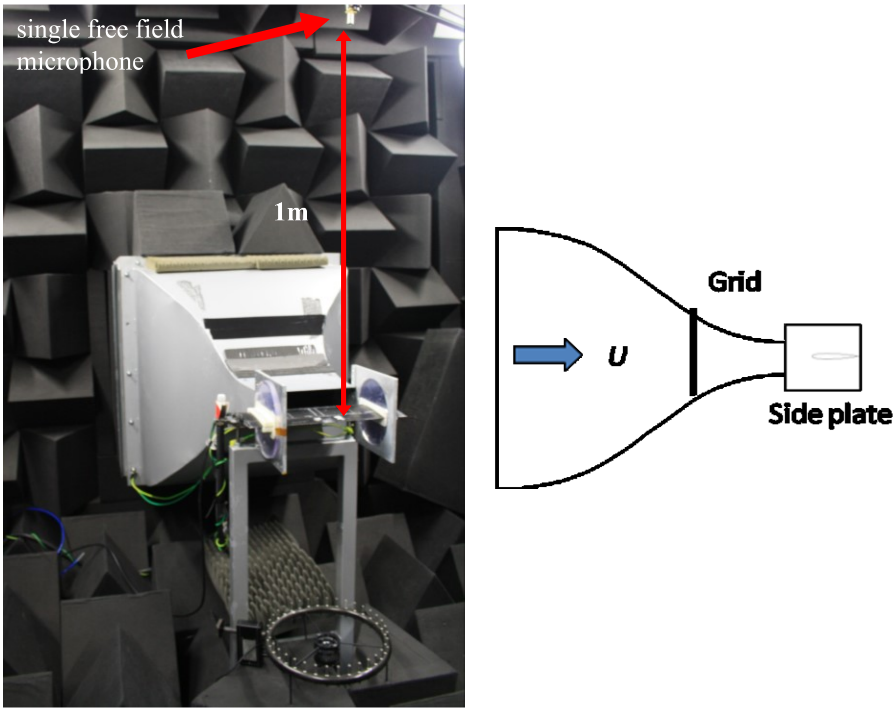


Fig. 2 Experimental set up for the airfoil noise tests in an aeroacoustic wind tunnel facility.

respectively. Although not shown in this paper, reasonably isotropic turbulence has been achieved under the current configuration (7).

As shown in Fig. 2, far field noise measurements were made by a single condenser microphone at polar angles of 90^{o} at a distance of 1.0 m from the aerofoil leading edge at mid span. Noise data was acquired at a sampling frequency of 44 kHz for 15 seconds by a 16-bit Analogue-Digital card from National Instrument. The data was then windowed and the Power Spectral Density (PSD) of 1 Hz bandwidth computed from a 1024 point FFT.

(a)

(b)

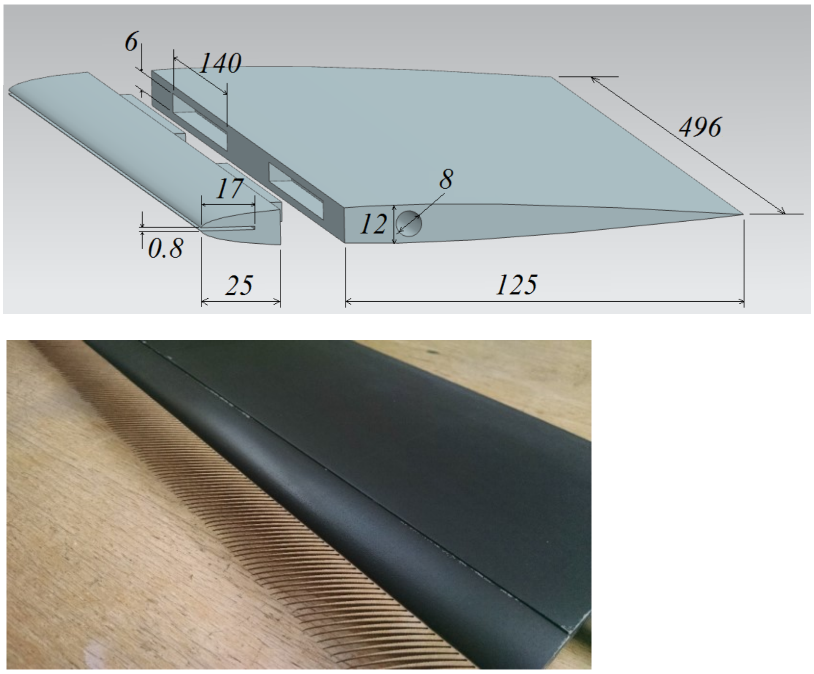


Fig. 3 (a) CAD model of the aerofoil assembly (dimensions in mm), (b) a leading edge curved serration on a NACA0008 aerofoil

2.2 Aerofoil Model and the Serrated Leading Edge Designs

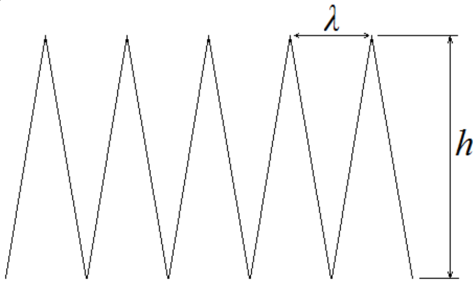
Since very few researches focus on the investigation of noise on thin aerofoils, symmetrical NACA0008 aerofoil has been selected in this study. As shown in Fig. 3, the aerofoil has a thickness to chord ratio t/C = 8%, giving a maximum aerofoil thickness of 12 mm for the current chord length C = 150 mm, with a span b = 496mm. The aerofoil has been designed so that the first 25 mm of the body (starting from the leading edge) can be detached. Thus, one of the detachable leading edges provides a straight leading edge to serve as a 'clean' aerofoil shape, hereafter referred to as the baseline aerofoil. The other detachable leading edge incorporates a slot with thickness = 0.8 mm and inner-length of 17 mm that runs along the chord line of the aerofoil. The slot allows various flat plate serrations to be slotted in and interchanged with other flat plate serrations easily. The flat plate serrations were laser-cut precisely. Cardboard sheets of ~ 0.8 mm thickness have been used. This material can achieve sufficient accuracy in terms of serration dimensions and provide the required stiffness.

The first type of serrations is the regular, straight sawtooth serrations shown in Figure 4a. To gain a better understanding of the effect of serration geometry on the aeroacoustic performance, a wide range of serration geometries was designed. There are two main design parameters: serration amplitude h and wavelength λ as shown in Figure 4a. The serration dimensions that have been chosen are as follows: 1) five wavelengths λ of 2.5, 5, 10, 15 and 20 mm, and 2) five amplitudes h of 5, 10, 15, 20 and 30 mm. The total combination results in 25 serrated leading edges. For the naming purpose, a serrated leading edge with λ = 2.5 mm and h = 15 mm will be represented by $\lambda 2.5h15$, and so on.

Note that the serrated leading edges were compared with the baseline leading edge of the same wetted area. For example, a serrated leading edge with h = 20 mm will be compared with a straight leading edge of h = 10 mm, and so on.

For the curved serrations, they have been manufactured in a similar way as the straight serration. As shown in Fig. 4b, the curved serration designs are based on four main geometric parameters: the serration amplitude h, wavelength λ, curvature radius R (where larger serration curvature is characterised by a smaller radius R) and inclination angle Θ. In the current study, the curved serrations are designed to have two radii R of 50 mm and 100 mm, and two inclination angles Θ of 15° and 30°. These variations in R and Θ allow for a reasonable wide range of geometrical change, thus allow the generalisation of the curvature effect on the aeroacoustic performances. It is also worth pointing out that the values for R = 50 mm and Θ = 15° provide a serration pattern that is quite similar to those found in the owl's wings.

(a)



(b)

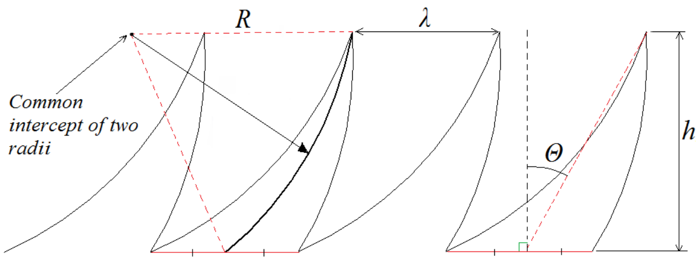


Fig. 4 Geometrical parameters for (a) straight sawtooth serrations, (b) curved sawtooth serrations

3. RESULTS

3.1 Straight Sawtooth Serrations

Since an elevated freestream turbulence intensity is analogous to placing boundary layer tripping element on the aerofoil surface, laminar instability tonal noise is not expected to be dominant in the current study. To confirm this, noise measurement was conducted for a tripped and untripped aerofoil for the baseline and a serrated aerofoil. Aerofoil tripping ensures that a turbulent boundary layer is formed across the aerofoil surfaces. The results are presented in the form of ΔSPL as a function of

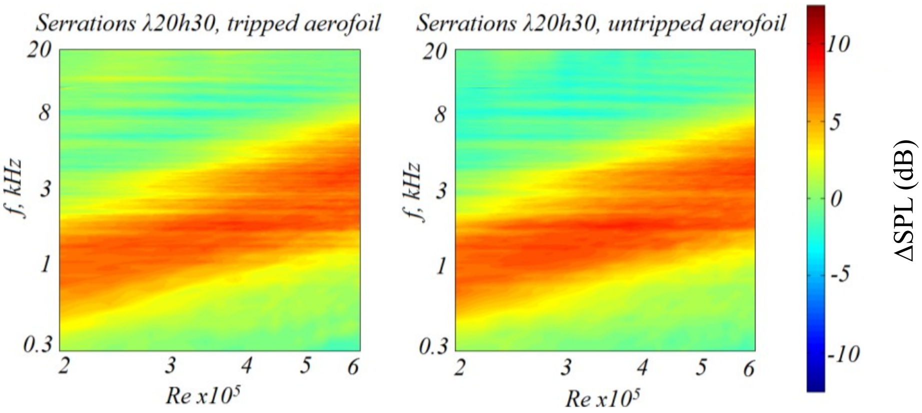


Fig. 5 ΔSPL contour maps for tripped (left) and untripped (right) aerofoil

frequency and Reynolds number. Here, ΔSPL is the difference of Sound Pressure Level (SPL) between the baseline aerofoil and serrated aerofoil. Therefore, a positive ΔSPL denotes noise reduction, and the opposite is true. Figure 5 shows that the difference between the untripped and tripped cases is small. This implies that the ΔSPL contours presented throughout the paper is mostly related to the reduction (or increase) in leading edge noise.

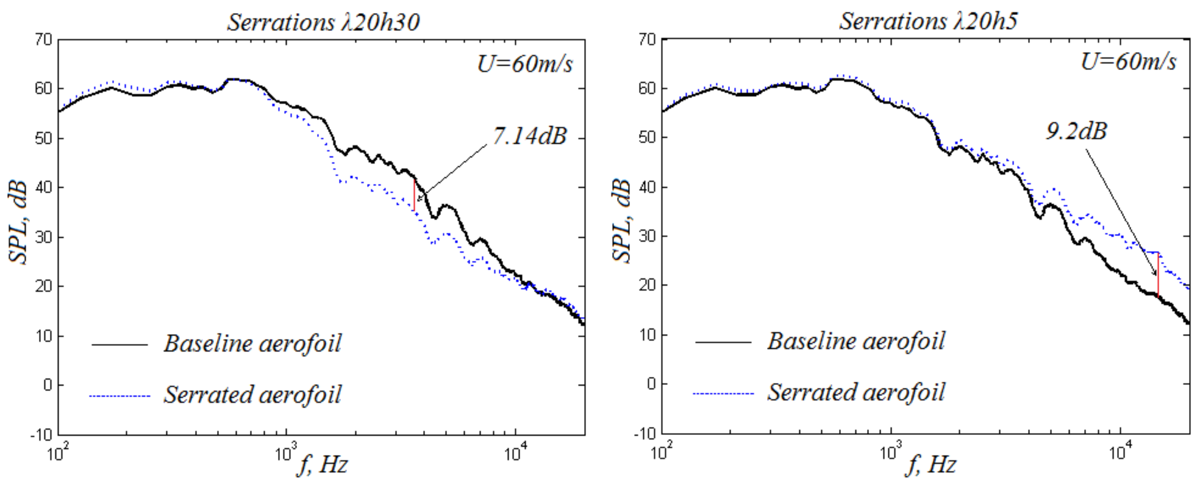


Fig. 6 Comparisons of SPL spectra between the baseline and serrated leading edges

Figure 6 compares the SPL spectra of $\lambda20h30$ and $\lambda20h5$ sawtooth serrations against the baseline aerofoil at $U_\infty = 60$ ms^{-1} (Re = 6 x 10^5). It can be seen that all the spectra exhibit a typical broadband characteristic at low frequency, indicating that the measured spectra are mainly the turbulent–leading edge interaction noise. The largest noise reduction of about 7.1 dB is by serration $\lambda20h30$ at 3.7 kHz. On the contrary, a poor performance is exhibited by the serration $\lambda20h5$ where large level of noise increase of 9.2 dB occurs at 14.7 kHz. Results in Fig. 6 provide a hint that the noise performance of the serrations can be quite sensitive to the choice of the serration amplitude h, as well as the wavelength λ.

Figure 7 demonstrates the ΔSPL contours of 25 sawtooth serration designs with different combinations of λ and h. It is apparent that the two governing geometric parameters of the serrations, λ and h, have significant effects on the noise reduction capabilities of the aerofoil. It was found that a small λ and large h improves the noise performance. Two extreme serration cases are compared: $\lambda2.5h30$ versus $\lambda20h5$. Serration $\lambda2.5h30$ achieved the largest level of broadband noise reductions in the range of 7–9 dB. Between Reynolds numbers of 4 to 6 x 10^5, the frequency bandwidth of the positive ΔSPL is about 1 kHz. Additional 2–3 dB broadband noise reductions tend to take up larger frequency bands of 0.64–2.7 kHz ($\Delta f \approx 2$ kHz) at Re = 2 x 10^5, to 1.6–8.9 kHz ($\Delta f \approx 7$ kHz) at Re = 6 x 10^5. The mechanism through which all the reductions are achieved is likely to be caused by the so

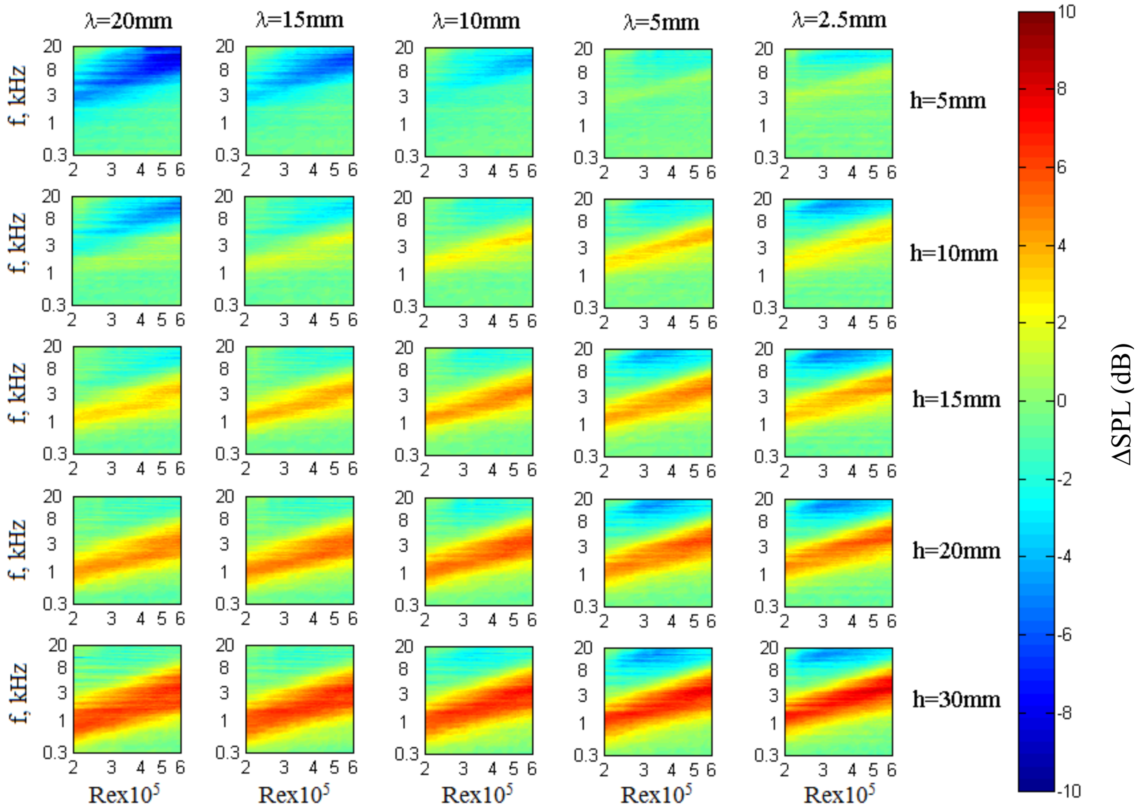


Fig. 7 ΔSPL contours produced by the straight sawtooth leading edge of different serration wavelengths λ, and serration amplitudes h.

called 'vortex trapping' mechanism, where the serrations act as a 'filter' for the incoming turbulent flow. As the incoming turbulent freestream flow hits the serrations at a very small angle β normal to the serration, as shown in Fig. 8a, the turbulent eddies are forced to 'stretch' in the direction of freestream flow, resulting in a lower turbulence intensity and reduced level of broadband noise radiation.

The other extreme serration case is $\lambda 20h5$ which demonstrates significant noise increase of 5–8 dB in the higher frequency range (from 2 to 20 kHZ) throughout the whole range of Reynolds number. Furthermore, up to 9–10 dB increase in noise is observed in the frequency range of 8 to 20kHz at Reynolds numbers in excess of 5x10^5. One possible explanation is the effect of serration geometry – since the serration has the largest wavelength and smallest amplitude, freestream flow impinges the serration at a larger angle β in comparison to, for example, $\lambda 20h30$ described earlier (compare Fig. 8a to Fig. 8b). It can therefore be postulated that the flow might see these particular serrations not as a leading edge modification that acts as a 'filter' for the incoming turbulent flow, but rather as an increase in aerofoil leading edge sharpness (or decrease in aerofoil thickness and leading edge radius). Similar observations can also be made for the serrations $\lambda 15h5$ and $\lambda 10h5$, although the high frequency noise increase diminishes with decreasing serration wavelength (or decreasing angle β).

The serration $\lambda 20h30$ demonstrates outstanding performance, since they can provide noise reductions of 4–7 dB in a broad frequency bandwidth of 0.4–2.1 kHz

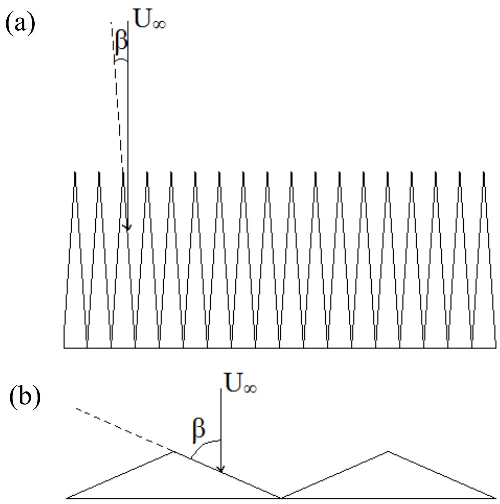


Fig. 8 Schematics depicting the angle β between the incoming flow and the serration oblique edges of (a) small wavelength, and (b) large wavelength

($\Delta f \approx 1.7$ kHz) at Re = $2\text{x}10^5$, to 1.2–8.8 kHz ($\Delta f \approx 7.6$ kHz) at Re = $6\text{x}10^5$. This indicates that in the case of serrations with h = 30 mm, the noise reduction performance experiences a significant boost at higher Reynolds numbers. Furthermore, this serration design has shown an excellent performance, since, contrary to the $\lambda 2.5h30$ case, it only generates very minor increase in the high frequency noise.

Another observation is the high frequency noise increase related to serrations with smaller wavelengths λ. This might be caused by the so called air 'leakage' that is normally related to high frequency noise increase. As the amplitude of serrations is increased, the relative distance between the successive serrations at the region closer to the serration through is decreased. Therefore, the freestream flow is forced to pass through a relatively small passage, hence generating high frequency aerodynamic noise due to the 'leakage' effect. As shown in Fig. 7, an opposite trend is observed with serrations having a wavelength λ of 20 mm. Due to the larger relative distance between the successive serrations at the region closer to the troughs of the serrations, these serrations do not suffer from the 'leakage' effect, but rather from the phenomenon where the angle β between the serrations and the freestream flow leads to an increase in noise, as outlined earlier. Therefore, at large wavelength, no significant high frequency noise increase is observed when the serration amplitude is increased.

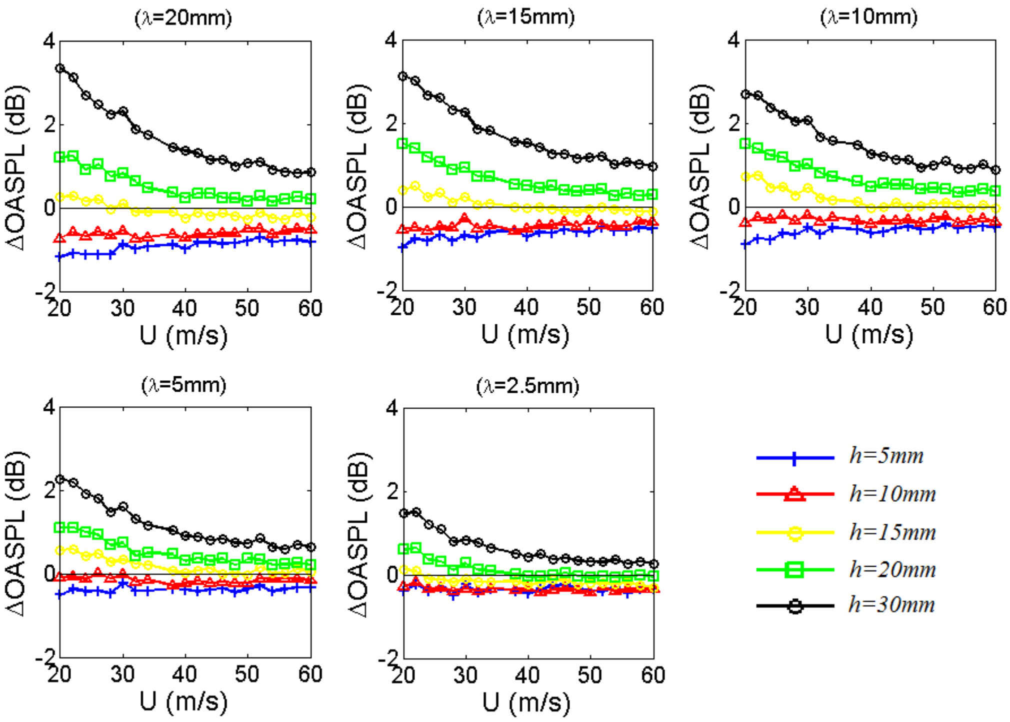


Fig. 9 ΔOASPL produced by straight sawtooth leading edges of different serration wavelengths λ, and serration amplitudes h.

It is generally observed that the level of noise reduction is the most sensitive to the serration amplitude. To examine the overall effect, the overall sound pressure level OASPL is calculated and difference between the baseline case and the serrated case (ΔOASPL) is plotted in Fig. 9 for different serration amplitudes and wavelengths. Similarly, a positive ΔOASPL denotes noise reduction, and vice versa. It can be seen that the sensitivity of the noise performance with relative to the serration amplitude gradually decreases when the serration wavelength is decreased. The ΔOASPL plots provide a good indication on the overall performance of the serrations. It can be seen that although serration $\lambda 2.5h30$ has shown the largest level of noise reduction in SPL, the maximum ΔOASPL is only about 1.5 dB at Re = $2\text{x}10^5$ since the generation of large level of high frequency noise reduces the overall noise performance of this serration design. The serration $\lambda 20h30$, however, can achieve an ΔOASPL of about 3.4 dB at the same Reynolds number. This is due to the absence of high frequency noise increase for this particular serration design. The ΔOASPL results also highlight another observation in terms of the noise reduction capability. It can be seen that the serrations tend to undergo decrease in performance with increasing freestream velocity U_∞ (also the Reynolds number). The

ΔOASPL decreases from 3.4 dB at U_∞ = 20 ms^{-1} (Re = 2 x 10^5) to 0.9 dB at U_∞ = 60 ms^{-1} (Re = 6 x 10^5) for the best performing serration $\lambda 20h30$. For the serrations with smaller wavelengths, the level of change is even larger. Therefore, it can be stated that while performing the best in the ΔOASPL, serration $\lambda 20h30$ also demonstrates better performance stability with the Reynolds numbers.

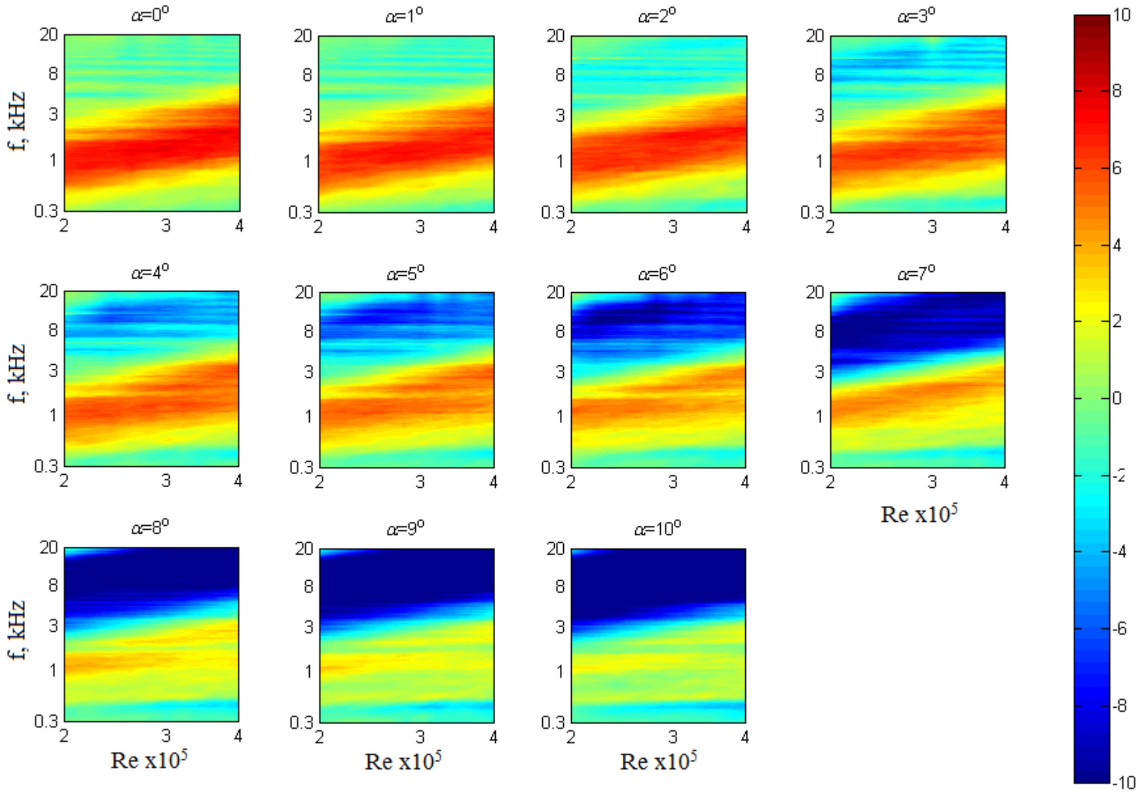


Fig. 10 ΔSPL contours produced by the straight sawtooth leading edge ($\lambda 20h30$) at different angles of attack (α).

3.2 Straight Serration at Different Angles of Attacks (Geometrical), α

It has been shown that the leading edge serration that can achieve the most reduction in the broadband noise level is the $\lambda 20h30$ type. In this section, this serration is chosen to investigate the effect when the aerofoil is subjected to different angles of attack, α. Noise measurements were taken with the aerofoil placed in the freestream flow at geometric angles of attack α ranging from 0° to 10° across a Reynolds number range of 2 x10^5 to 4x10^5. The reason for not investigating at higher Reynolds number is due to the consideration that fluttering might start to occur for the flat plate devices. Contour maps of ΔSPL between a baseline and serrated ($\lambda 20h30$) aerofoil, as a function of Reynolds number and frequency, are shown in Fig. 10.

As the geometrical angle of attack is increased, minor changes are observed up to $\alpha = 2°$ due to the relatively low ‘effective’ angle of attack. At $\alpha \geq 3°$, the level of broadband noise reduction, as well as their frequency bandwidth start to decrease, and at the same time the increase in high frequency noise becomes more prominent. Between $\alpha = 9°$ and 10°, the level of broadband noise reduction becomes very low, whilst significant noise increase is found at the high frequency region.

3.3 Curved Sawtooth Serrations

A flat plate straight sawtooth serration has been shown to produce good performance in the broadband noise reduction. However, some drawbacks have also been observed, most notably the penalties in high frequency noise increases. The next step is to modify the serration to alleviate the problem of high frequency noise increase. A ‘curved’ serration design, inspired by the serrations found in the leading edge of an owl, is developed here. In the following discussion, the extra two geometric

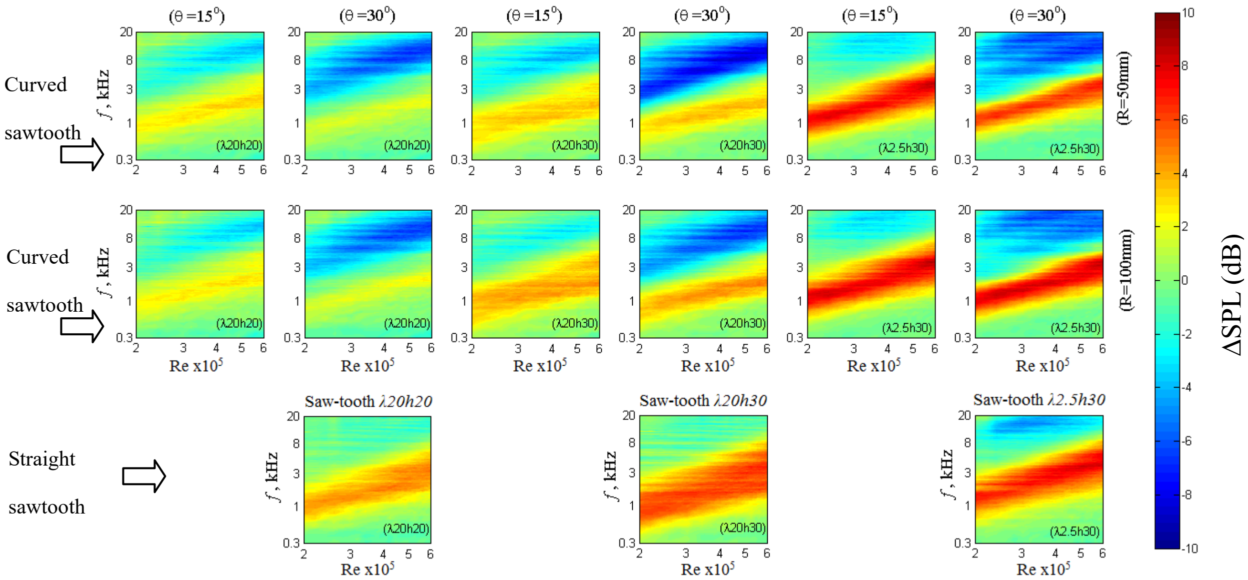


Fig. 11 Comparison of ΔSPL contours produced by leading edges with the curved sawtooth serrations and straight sawtooth serrations sawtooth.

parameters that could be used to describe a curved serration are the curvature R and inclination angle Θ. Similarly, the test condition covers Reynolds number between 2x10^5 and 6x10^5, and at $\alpha = 0^o$ only. Contour maps of ΔSPL between the baseline and the curved serrations, as a function of Reynolds number and frequency, are shown in Fig. 11.

"Curving" the serration is still found to result in high frequency noise increase for most of the cases. For the $\lambda 20h20$ case, the broadband noise reduction capability otherwise exhibits in a straight serration is even weakened considerably in the curved serration. It can be seen that for the curved serrations of $\lambda 20h20$, $\lambda 20h30$ and $\lambda 2.5h30$, reducing R (or increasing serration curvature) at a particular inclination angle Θ will produce only slight changes in the high frequency noise increase.

An exception is found for the $\lambda 2.5h30$ case with Θ = 15 degree. This curved-configuration is regarded as the best in terms of successfully reducing the level of noise increase at high frequency if compared the straight serration counterpart. In addition, the level of broadband noise reduction for both the curved and straight sawtooth serrations remains similar. Therefore, in order for serration inclination and curvature to have a positive effect on the aeroacoustic performance, the serration is required to have a small wavelength λ.

Another interesting trend for the curved serrations is the sensitivity of high frequency noise to the inclination angles Θ. Generally, when Θ increases, all the curved serrations produce higher level of noise increase at high frequency. Current results suggest that serrations with smaller inclination angle Θ produce lower level of noise increase at high frequency, but it can also degrade slightly the frequency bandwidth underpinning the broadband noise reduction.

When curvature is applied to the serrations, the curved-passage between the serrations could not effectively "shield" the incoming turbulence from impinging the serration trough regions. Instead, the incoming flow direction is now mainly guided by the curvature of each serration as demonstrated in Fig. 12. Such cross flow could induce additional mixing of the flow within the serration region, thereby inducing higher levels of turbulence which then impinges on the serration edge and troughs. Although the curved serrations have been shown to be beneficial in reducing the high frequency noise when the wavelength λ is small, they also tend to have poorer performance than the straight sawtooth serrations on the level and frequency bandwidth of the broadband noise reduction.

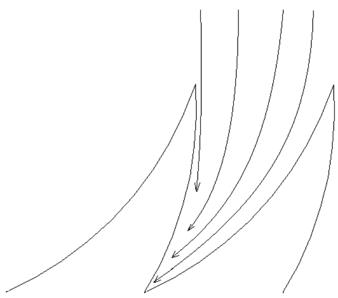


Fig. 12 Schematic showing the deflected incoming flow direction approaching the curved sawtooth serration.

4. CONCLUSIONS

This paper presents the results of an experimental investigation of the effect of add-on type leading edge serrations on the aeroacoustic performance of a symmetrical NACA0008 aerofoil. The focus is on the turbulence-leading edge interaction noise. Tests have been conducted in an aeroacoustic open jet wind tunnel. Several leading edge sawtooth serrations, generally those having larger amplitudes, have shown the ability to reduce broadband noise levels as much as 10 dB at certain frequency bands. However, serration designs with smaller amplitude have shown noticeable levels of noise increase at high frequency. Application of the bio-inspired curved serration geometry in most cases produces no significant difference when compared with the non-curved serration designs, although in certain cases further reduction in noise level at high frequency region can be observed. At increasing angles of attack, the effectiveness of the sawtooth serrations deteriorates significantly. At the largest angle of attack, the level of broadband noise reduction is significantly lowered, and at the same time noise increase at high frequency (up to 10 dB with a large frequency bandwidth) is present. Overall, the add-on type leading edge serration concept still demonstrates considerable interaction broadband noise reduction capabilities if the right serration amplitudes and wavelengths are chosen.

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