REDUCTION OF FLOW INDUCED AIRFOIL TONAL NOISE USING LEADING EDGE SINUSOIDAL MODIFICATIONS

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Significant tonal noise reduction has been achieved using sinusoidal protuberances, also known as tubercles, on the leading edge of a NACA 0021 airfoil for a Reynolds number, Re ~ 120,000. It has also been observed that the overall broadband noise is reduced for a considerable range of frequencies surrounding the peak in tonal noise. It is postulated that tonal noise elimination is facilitated by the presence of streamwise vortices generated by the tubercles and that the spanwise variation in separation location is also an important factor. Both characteristics modify the boundary layer stability, altering the frequency of velocity fluctuations in the shear layer near the trailing edge. This affects the coherence of the vortex generation downstream of the trailing edge, hence leading to a decrease in trailing edge noise generation. An additional effect is the confinement of the suction surface separation bubble to the troughs between tubercles, which may reduce the boundary layer receptivity to external acoustic excitation. Investigations have also revealed that the smallest wavelength and largest amplitude tubercle configuration have the lowest associated tonal and broadband noise

INTRODUCTION

The presence of leading edge tubercles gives rise to several flow effects which could reduce or eliminate tonal noise. For example, the generation of streamwise vortices reduces the coherence of the wake [1] and several researchers have shown evidence of this streamwise vortex formation [2-4]. Furthermore, it has been observed that due to varying locations of separation along the span-wise direction, the separation line becomes somewhat interrupted [3]. This would also lessen the coherence of vortex shedding in the wake. According to Nash et al. [5], airfoil tonal noise is associated with the vortex shedding process and the von Kármán vortex street is shed with the same frequency as the acoustic tone. Suppression of the von Kármán vortex street formation and associated reduction of acoustic disturbance intensity was discussed by Kuethe [6] in relation to vortex generators which generate a similar disturbance to the flow as tubercles.

Other methods of tonal noise reduction and/or elimination include leading edge serrations and boundary layer trips. The acoustic effect of leading edge serrations on a NACA 0012 airfoil was investigated by Hersch et al. [7]. These researchers observed that tones were produced by periodic fluctuating forces, acting on the airfoil near the trailing edge as a result of forces induced by wake vortex shedding. It was found that the serrations caused formation of streamwise vortices on the airfoil suction surface whilst simultaneously tripping the boundary layer on the pressure surface to turbulence. These effects eliminated virtually all tones by changing the wake vortex structure from periodic to random. Arndt and Nagel [8] made similar observations regarding the considerable reduction of tonal noise with leading edge serrations. The effect was attributed to vortex generation caused by the presence of the serrations, which reduced wake-induced tonal noise. A further method of tonal noise elimination summarised by Nash et al. [5] is through placement of a boundary layer trip on the pressure surface of an airfoil sufficiently far from the trailing edge (i.e. less than 80% chord from the leading edge).

The distinct advantage of tubercles is that the tonal noise reduction is coupled with aerodynamic benefits such as increased maximum lift coefficient and maximum stall angle [9]. In addition, tubercles promote more gradual stall characteristics as well as increased lift post-stall [10]. Noise reduction has been identified as a potential benefit associated with tubercles [11] however there have been no previous studies of the effect of tubercles on airfoil self-noise. This is an important issue, because if aspects of tubercles were to be incorporated into new hydrofoil, airfoil and rotor designs, then it is important to firstly understand how noise is modified, and secondly, to exploit any noise-reduction capability that they may have. Airfoil tonal noise has been identified as a potential problem for wind turbines, gliders, small aircraft, rotors and fans [12, 13]. According to McAlpine et al. [12], tonal noise also occurs in underwater applications such as hydrofoils and propellers and is quite common on fast yachts and dinghys.

Tonal noise generation is believed to be initiated by Tollmein-Schlichting instabilities in a laminar boundary layer [5, 14, 15], which become amplified at the airfoil trailing edge [14] or at a point nearby [12]. Many researchers concur that a necessary condition for the generation of tonal noise is the existence of a self-excited acoustic feedback loop [14-17], however, there are various theories as to its nature and position. More specifically, some researchers suggest that the noise source is at the trailing edge and that the feedback loop exists between this point and a critical point upstream in the boundary layer [16, 17]. On the other hand, some researchers maintain that the acoustic source is in the wake and that the feedback loop extends from here to the critical point in the boundary layer [14, 15].

The aim of this paper is to present the results from an experimental investigation into the effects of sinusoidal leading edge modifications on airfoil self-noise for a NACA 0021 airfoil at low-to-moderate Reynolds numbers. The ability of tubercles to eliminate tonal noise is demonstrated for both a closed section wind tunnel and an anechoic wind tunnel. A further aim of this paper is to investigate the relationship between the tonal noise frequency and the separation characteristics in order to shed light on the mechanism of airfoil tonal noise generation.

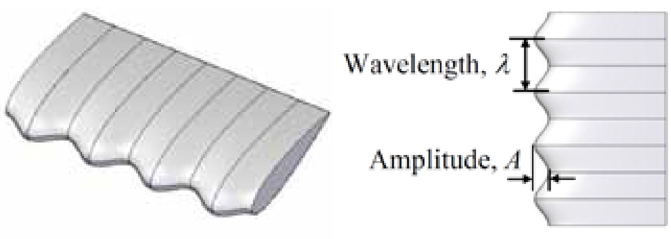
EXPERIMENTAL METHODS

Airfoil Design

Tubercle configurations were incorporated into a NACA 0021 airfoil profile and a baseline airfoil was manufactured for comparison. Airfoils were machined from aluminium and all airfoils have a chord of c = 70mm and span of s = 495mm, giving a plan-form area of S = 0.035m^2. The limited width of the anechoic wind tunnel, restricted the span to s = 275mm, giving a corresponding plan-form area, S = 0.019m^2. Sinusoidal tubercle configurations are summarised in Table 1 and the dimensions are illustrated in Fig. 1.

Table 1. Tubercle configurations and adopted terminology

Configuration	Label	A/λ Ratio
0021 unmodified	0021 unmod	-
A = 2mm (0.03c) λ = 7.5mm (0.11c)	$A2\lambda7.5$	0.27
A = 4mm (0.06c) λ = 7.5mm (0.11c)	$A4\lambda7.5$	0.53
A = 4mm (0.06c) λ = 15mm (0.21c)	$A4\lambda15$	0.27
A = 4mm (0.06c) λ = 30mm (0.43c)	$A4\lambda30$	0.13
A = 4mm (0.06c) λ = 60mm (0.86c)	$A4\lambda60$	0.07
A = 8mm (0.11c) λ = 30mm (0.43c)	$A8\lambda30$	0.27



(a) (b)

Figure 1. Section view of airfoil with tubercles (a) 3D view, (b) Plan view with characteristic dimensions

Acoustic and Pressure Tapping Measurements

Acoustic and pressure tapping measurements were carried out using a low-speed wind tunnel at the University of Adelaide, which has a 0.5m square cross-section and a turbulence intensity of $TI \sim 0.8\%$. The working section shown in Fig. 2 was bolted to the exit of the wind tunnel and the top of the airfoil was located very close (3mm) to the ceiling of the duct to minimise three-dimensional effects. The free-stream velocity was measured using a Pitot tube and the Reynolds number was Re = 120,000, based on the free-stream velocity of U_∞ = 25m/s and airfoil chord length of c = 70mm. The working section did not have any form of acoustic treatment.

For the acoustic measurements, the microphones were arranged according to Fig. 2 and were fixed in the same positions for all experiments. In the case of the pressure measurements, static pressure ports were incorporated into both the unmodified and modified airfoils at the positions shown in Fig. 3 to observe the surface pressures. The small thickness of the airfoils increased the complexity of incorporating pressure taps into the existing models. Hence, it was decided that it would be more feasible to manufacture airfoils using a casting technique whereby the pressure taps could be moulded into the design during fabrication.

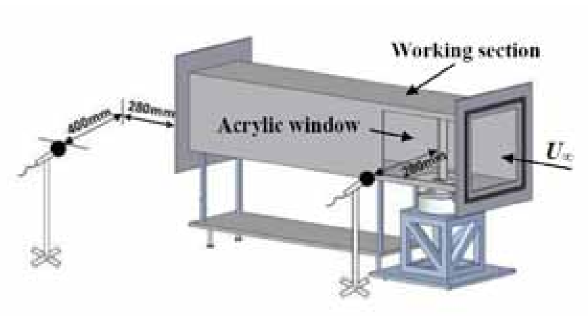


Figure 2. Working section and microphone positions

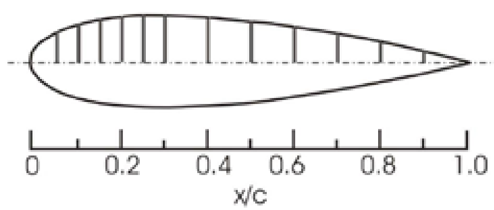


Figure 3. Pressure tap locations for unmodified airfoils

Pressures at the airfoil surface were received by a Scanivalve mechanical pressure multiplexer, model number: 48D3-1404A which was connected to a controller. The output from the Scanivalve was received by a Baratron pressure transducer. The system was controlled using a Labview program which was written to interface with a data logger. A time delay of 5s was included to allow the pressure to stabilise at a given location before the commencement of data acquisition. Measurement duration was 30s, which was followed by another time delay of 5s to eliminate the uncertainties caused by advancement of the Scanivalve to the next position.

Further acoustic results were obtained using the anechoic wind tunnel (AWT) at the University of Adelaide, which has a room size of approximately 2m^3 and walls acoustically treated with foam wedges. The contraction outlet has dimensions of 75mm (height) and 275mm (width). End-plates were manufactured for the model to reduce three-dimensional effects and a circular cut-out section with a 'running fit' tolerance allowed the angle of attack to be adjusted as shown in Fig. 4.

The Reynolds number was $Re = 120{,}000$, based on the free-stream velocity of $U_\infty = 25$m/s and airfoil chord length. At this freestream velocity, the corresponding turbulence intensity is $TI \sim 0.4\%$. For these measurements, a single microphone was positioned at a height of 650mm above the airfoil trailing edge and 50mm posterior to the trailing edge.

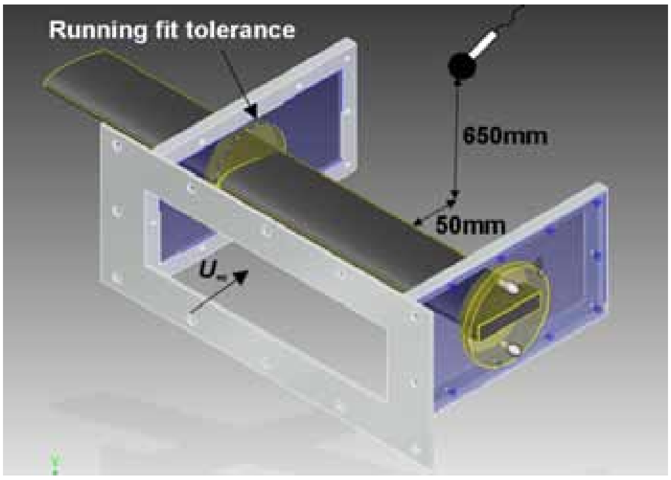


Figure 4. Mount for anechoic wind tunnel

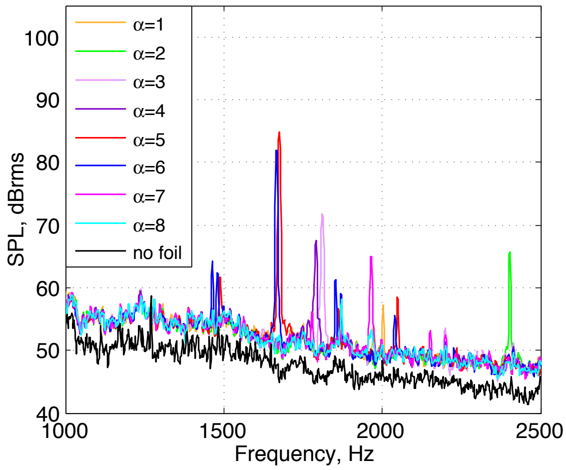
RESULTS AND DISCUSSION

Acoustic Measurements in Hard-Walled Wind Tunnel (HWT)

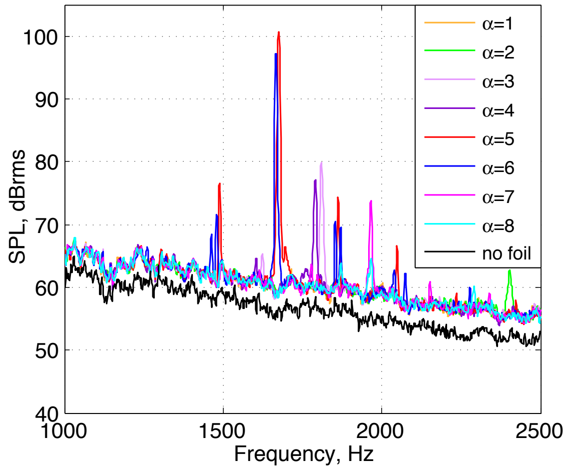
Tonal noise measurements were initially conducted in the hard-walled wind tunnel (HWT) since it was observed that there was an audible difference in tonal noise between models with and without tubercles. Hence, it could be argued that the difference in noise levels was large enough to be measured. The influence of the duct on tonal noise propagation was monitored through comparing the results from two microphones positioned at different streamwise locations. Measurement of the duct modes was not considered pertinent to the investigation because the leading edge tubercles did not change the reflecting surface of the airfoil significantly. Therefore, significant differences in tonal noise for airfoils with and without tubercles were attributed to altered flow characteristics associated with the presence of tubercles. Nevertheless, it should be noted that the absolute values presented in Fig.5 are affected by the highly reverberant nature of the duct and that the relative difference in SPL between the tonal peaks and the broadband noise is more meaningful.

At each angle of attack from $\alpha = 1°$ to $\alpha = 8°$, the unmodified NACA 0021 airfoil generates tonal noise as shown in Fig. 5(a) and (b). According to McAlpine et al. [12], tonal noise would not occur if transition to turbulence occurred sufficiently far from the airfoil trailing edge, which is a possible explanation for the absence of tones for $\alpha > 8°$.

Results are shown for both microphones and it can be seen that the sound pressure level (SPL) at the duct exit is higher due to the transmission loss associated with the acrylic window. There are some slight variations in the two sets of results which can be attributed to the variation in sound directivity with frequency.



(a)



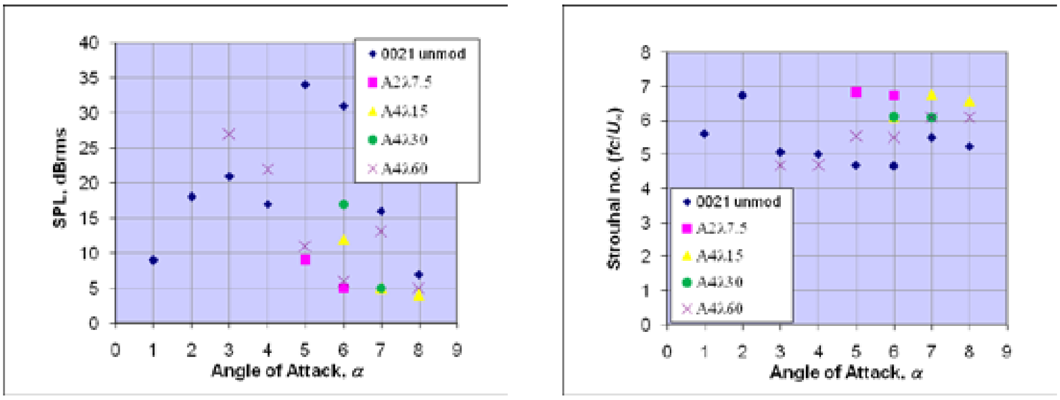
(b)

Figure 5. Sound pressure level (SPL) against frequency, f, for NACA 0021 at angle of attack, α = 1°-8°, Re = 120,000 (a) microphone at window, (b) microphone at exit

The results shown in Fig. 6(a) indicate that for airfoils with tubercles, there is a substantial reduction in SPL and that in general, the Strouhal number of the tonal noise is higher for airfoils with tubercles as evident in Fig. 6(b). The Strouhal number, St is defined according to Eq. (1)

$$St = \frac{f\,c}{U_\infty} \tag{1}$$

where f is the frequency of tone, c is the airfoil chord and U_∞ is the freestream velocity.



(a) (b)

Figure 6. Results at microphone nearest window for NACA 0021 airfoils with tubercles at $1° \leq \alpha \leq 8°$. (a) Sound pressure level (SPL) against angle of attack, α and (b) Strouhal number against angle of attack, α

The largest amplitude tubercles, $A8\lambda30$, and the smallest wavelength case, $A4\lambda7.5$, both of which have relatively large A/λ ratios are not included in the plots since they did not generate any detectable tonal noise. For the tubercle configurations shown in Fig. 6, the smallest wavelength case ($A2\lambda7.5$) has the highest Strouhal number and lowest SPL amplitude at the two angles of attack at which it produces tonal noise. The largest wavelength tubercle case ($A4\lambda60$) generates the tones at the lowest Strouhal number and for a greater number of attack angles and a higher SPL compared to the other airfoils. Note that the results in Fig. 6 were obtained by subtracting the broadband SPL for the corresponding angle of attack and frequency. In addition, only the largest amplitude tone was considered and thus secondary tones were not plotted.

Acoustic Measurements in Anechoic Wind Tunnel (AWT)

Referring to Fig. 7(b-g), it can be seen that all tubercle configurations experience significantly reduced SPL at the tonal frequency and in most cases the tonal noise is eliminated altogether. Consistent with the results in the HWT, the most successful tubercle configurations for tonal noise elimination are those with a larger value of A/λ ratio as shown in Fig. 7(b), (c), (d) and (g).

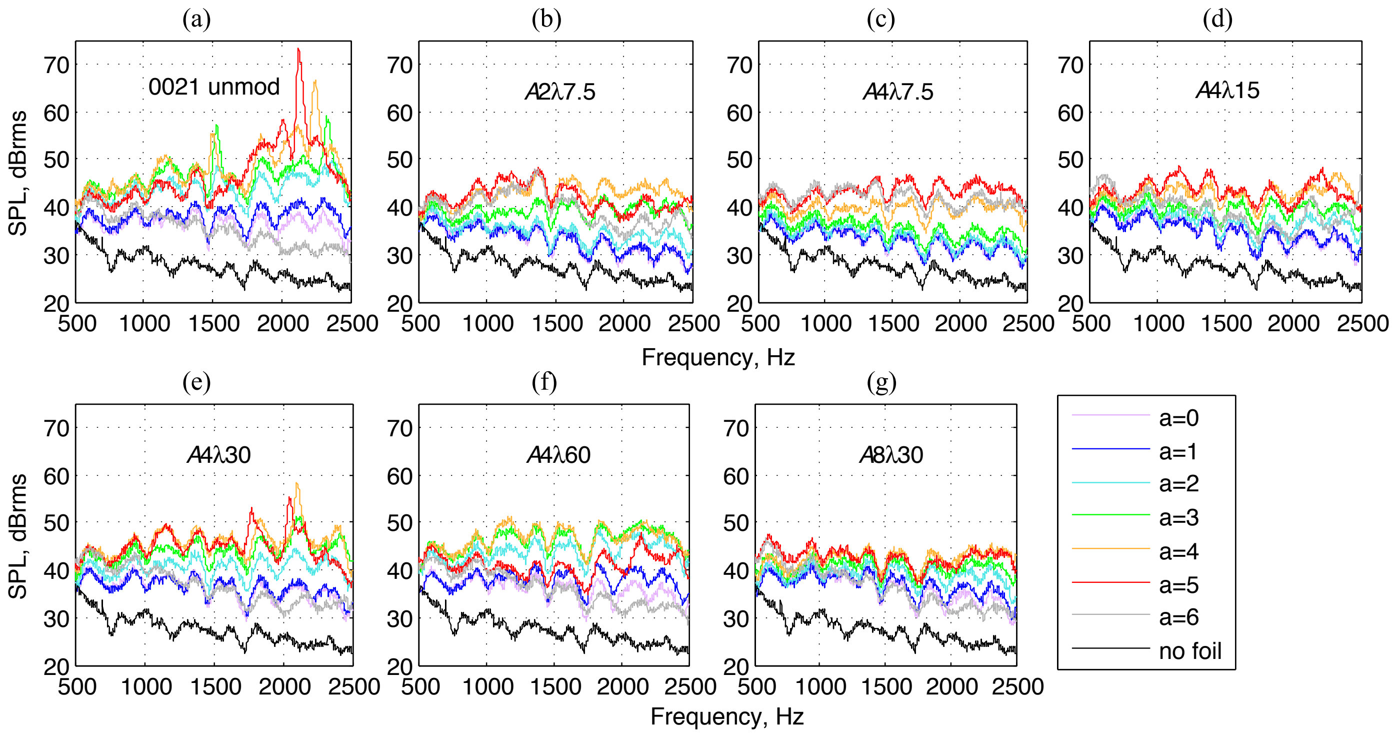


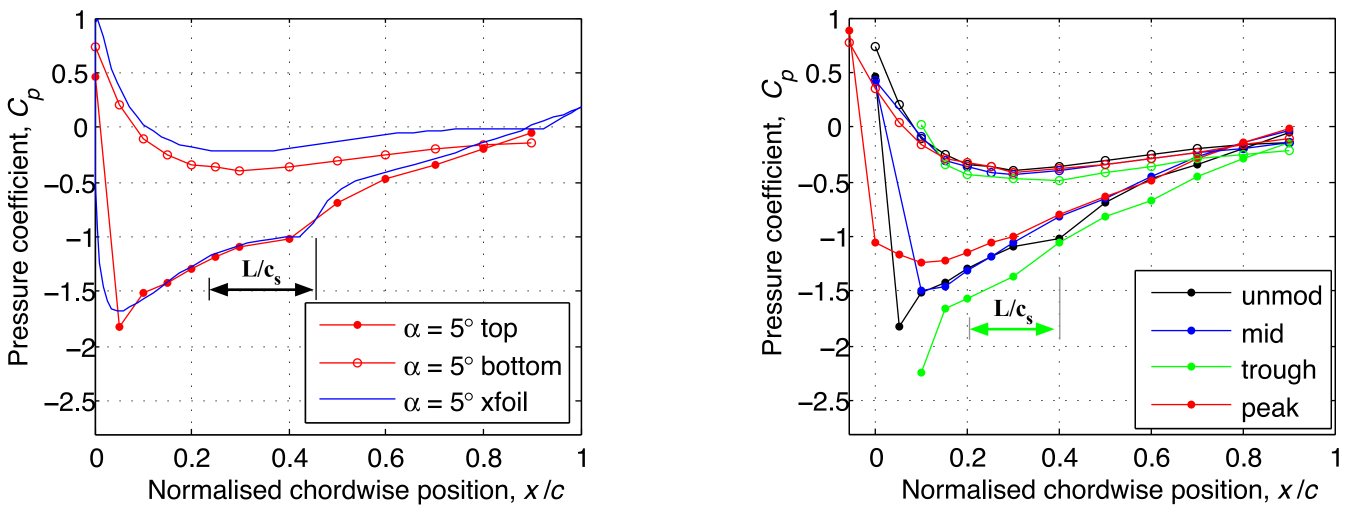
Figure 7. SPL against frequency measured in anechoic wind tunnel (AWT) for (a) unmodified 0021 (b) $A2\lambda7.5$ (c) $A4\lambda7.5$ (d) $A4\lambda15$ (e) $A4\lambda30$ (f) $A4\lambda60$ (g) $A8\lambda30$, $Re = 120{,}000$

Also, the largest amplitude tone for the unmodified airfoil occurs at $\alpha = 5^o$, which can be seen in Fig. 7(a) and is in agreement with the results discussed earlier for the HWT. However, the tonal frequency at this angle of attack is slightly higher in the AWT (2125Hz compared with 1675Hz in the HWT). This is an interesting discrepancy which highlights the sensitivity of the tonal noise generating mechanism to changes in experimental parameters, even after standard corrections have been applied to account for the downwash and flow curvature of the airflow around the model associated with the finite size of the open jet [18]. Another difference between the sets of results is that tonal noise appears over a much wider range of angles when testing in the HWT. A result that was not observable using the HWT is a small reduction in broadband noise, which occurs between 1500 and 2500Hz for all airfoils with tubercles. A higher broadband component appears to be directly related to the presence of the tones for the unmodified airfoil.

Pressure tapping results

The pressure coefficient, C_p, is plotted as a function of the normalised chordwise position for the NACA 0021 unmodified airfoil and the $A8\lambda30$ tubercle configuration in Fig 8. Experimental measurements are compared to values obtained using the XFOIL code [19].

The existence of a separation bubble is reflected in Fig. 8 for both the experimental and XFOIL data at $\alpha = 5°$ and is identified as the section of the suction curve where the pressure gradient starts to decrease, almost reaching a value of zero. After the separation bubble, the pressure gradient increases rapidly and then reaches the value which would be predicted in the absence of the separation bubble. The difference between the results for the unmodified airfoil and the airfoil with tubercles is that the separation bubble is localised to the troughs in the latter case rather than extending over the entire span as shown in Fig. 8(b). This is a possible explanation for the absence of tonal noise for airfoils with tubercles.



(a) (b)

Figure 8. Normalised pressure distribution plots for (a) unmodified airfoil and (b) airfoil with $A8\lambda30$ tubercle configuration at $\alpha = 5°$, where symbols are chosen as follows: "●" suction surface "○" pressure surface, $Re = 120{,}000$.

CONCLUSIONS

Incorporating tubercles into the leading edge of an airfoil facilitates the reduction and potential elimination of tonal noise for a NACA 0021 airfoil. In addition, the broadband noise is significantly reduced for a range of frequencies adjacent to the tonal peak. It is believed that the mechanism responsible involves the generation of streamwise vortices as well as the spanwise variation in separation location. Both effects alter the boundary layer stability characteristics, influencing the coherence of the vortices downstream from the trailing edge, hence reducing trailing edge noise generation. Also, confinement of separation bubbles to the troughs between tubercles reduces boundary layer receptivity to external acoustic excitation. Consequently, the potential for development of a feedback loop is minimised, which is another explanation for the significant reduction or absence of tonal noise for airfoils with tubercles.

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Inter-Noise 2014

MELBOURNE AUSTRALIA 16-19 NOVEMBER 2014

The Australian Acoustical Society will be hosting Inter-Noise 2014 in Melbourne, from 16-19 November 2014. The congress venue is the Melbourne Convention and Exhibition Centre which is superbly located on the banks of the Yarra River, just a short stroll from the central business district. Papers will cover all aspects of noise control, with additional workshops and an extensive equipment exhibition to support the technical program. The congress theme is *Improving the world through noise control*.

Key Dates

The proposed dates for Inter-Noise 2014 are:
Abstract submission deadline: 10 May 2014
Paper submission deadline: 25 July 2014
Early Bird Registration by: 25 July 2014

Registration Fees

The registration fees have tentatively been set as*:

Delegate	$840	$720 (early bird)
Student	$320	$255 (early bird)
Accompanying person	$140	

**An additional GST applies to Australian based delegates*

The registration fee will cover entrance to the opening and closing ceremonies, distinguished lectures, all technical sessions and the exhibition, as well as a book of abstracts and a CD containing the full papers.

The Congress organisers have included a light lunch as well as morning and afternoon tea or coffee as part of the registration fee. These refreshments will be provided in the vicinity of the technical exhibition which will be held in the Main Foyer.

The Congress Banquet is not included in the registration fee.

Technical Program

After the welcome and opening ceremony on Sunday 16 November, the following three days will involve 10 parallel sessions covering all fields of noise control. Major areas will include Community and Environmental Noise, Architectural Acoustics, Transport Noise and Vibration, Human Response and Effects of Low Frequencies and Underwater Noise. A series of distinguished lectures and workshops are planned to cover topics such as:

- Noise impact on high density living
- Impact on dense living
- Wind turbine noise
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