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Experimental investigation on noise emissions of an airfoil with non-flat plate trailing edge serrations [†]

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Abstract

This paper presents an experimental study on the aeroacoustic characteristics of a NACA 0018 with nonflat plate-type serrated trailing edge at Reynolds numbers of 500000 in an open-jet wind tunnel. The experimental results show that noise reduction can be achieved in the moderate frequency range for nonflat plate type triangular serrated trailing edges, but at the cost of producing narrowband tone noise. The level of the vortex shedding noise declines when serration length 2 h decreases. It is imperative that the vortex shedding tone noise be completely suppressed when a novel slanting root serrated trailing edge is adopted. Meanwhile, the ability of broadband noise reduction is maintained.

Keywords: Trailing edge serrations; Slanting root serration; Trailing edge noise

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1. Introduction

Noise emitted from the trailing edge of an airfoil blade is believed to be a major noise source in many industrial applications, such as cooling fan blades, air frames or wind turbines, to name a few. The mechanism of which is attributed to the interaction between an airfoil blade and the turbulence produced in its own boundary layer [1]. When turbulent fluctuations encounter a solid body with a sharp edge, a scatter process occurs more efficiently than in free-space (Ma^5 c.f. Ma^8), which leads to a considerable increase in the radiated sound power [2, 3], in particular for low Mach numbers flow. It poses a serious threat to human well-being and the environment in general. Therefore, there has been much interest in developing control methods aimed at reducing trailing edge noise [4].

Trailing edge noise can be reduced in an active way or in a passive way [5]. With regard to the passive techniques, it has long been recognized that geometry modification of the trailing edge, including serrated edges [6, 7], brushes [8, 9] and a porous surface [10], appears to be a fruitful strategy in reducing the trailing edge turbulent broadband noise. These approaches have been reported experimentally by a low speed rig test to achieve noise reductions between 3 and 7 dB, in which one of the promising geometry modification approaches is the trailing edge serration.

The noise reduction concept using a serrated trailing edge design was first proposed by Howe, who assumed that the serrations do not change the turbulence characteristics near the trailing edge [6, 7]. Howe studied analytically the trailing edge noise from a flat plate, with sinusoidal and sawtooth trailing edge, which is both defined by the wavelength of serrations λ and their amplitude h. These theoretical studies indicate [7] that the far-field noise can be reduced at low Mach number provided that the edges are inclined at an angle φ less than about $45°$. At frequencies satisfied in $\omega h / U \gg 1$ (U is the main stream velocity), the intensity of the radiation is reduced at least $10 \times \log\left[1+\left(4h/\lambda\right)^2\right]$ dB for sawtooth serrations and $10 \times \log\left(6h/\lambda\right)$ dB for sinusoidal serrations. Furthermore, Howe's theory argues that the serration geometry with narrower, sharper sawteeth would produce a greater noise reduction.

Following Howe's encouraging theoretical work, many experiments [11-15] have been carried out to evaluate the noise reducing benefits of serrated trailing edge; especially, a more recent experimental investigation by Gruber [14, 15] has indicated that the noise reduction effect can be improved using more complex trailing edges. These studies also indicate that the sharper the serration, the greater is the noise reduction,

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which is consistent with the theory of Howe. But noise reduction reported by all experimental tests [13-15] conducted on trailing-edge serrations in the past shows that some discrepancy arises between their observations and Howe's theory (≤ 7 dB seen in wind tunnel measurements compared to ≈ 12 dB over a select frequency range), which suggests the physical mechanisms of the serrations edge reduction noise are not fully understood.

In addition, previous works, except in the works by Chong and Joseph [4, 16], utilize a thin flat plate serrations inserted directly into the trailing edge, without considering the effect of the airfoil shape on the noise generation and propagation, which could potentially cause a modification of the pressure loading on the airfoil surfaces. Especially for a highly cambered airfoil, the level of the adverse pressure gradient encountered at the flat plate insert at the suction surface could be high enough to trigger turbulent separation and produce additional noise sources [4]. Moreover, the flat plate serration inserts are difficult to preserve the integrity of the structure for continuous operation under high load configuration. All of which might potentially limit the eventual and widespread adoption of sawtooth technology in the many industrial applications.

With regard to Chong and Joseph [16], the non-flat plate narrower trailing edge serrations, with the ratio of the serration period over the serration length (i.e. λ / h) varying from 0.49 to 1.87 and the root bluntness $\varepsilon = 5.7$ mm, is adopted. The angle of attack is set at $\alpha = 4.2°$. The experimental results show that it will inevitably produce narrowband noise due to vortex shedding from the blunt part of the serration at the root.

In this paper, we researched the noise emission of a non-flat plate type wider serrated trailing edge, with the ratio of the serration period over the serration length (i.e., λ / h) varying from 1.33 to 4, and the root bluntness ε varying from 6.22 mm to 17.30 mm, which benefits to increase the structural strength of the sawteeth. We gathered experimental evidence to show that, in the moderate broadband frequency range from 1500 Hz to 10 kHz, noise reductions can be obtained but at the cost of producing narrowband tone noise attributed to the vortex shedding that is generated by the bluntness at the root of the serration, which is similar to that of Chong [17]. For suppressing the vortex shedding tone noise, a poro-serrated modification was adopted by Chong. But in this paper, a new strategy with slanting root serrations of reducing the influence of this extraneous noise is presented. One of the main objectives was to investigate whether multiple-broadband noise reduction mechanisms can co-exist in the slanting root serrated trailing edge configuration.

In what follows, the experimental setup, the test model details and instrumentation are described in Sec. 2. Some experimental results and discussions are then described in Sec. 3. Conclusions close the paper in Sec. 4.

2. Experimental setup

Experiments were carried out in an open-jet-type low speed anechoic wind tunnel at the University of Shanghai for Science and Technology shown in Fig. 1. The test chamber of which is cubic, approximately 5.8 m × 4.3 m × 3.6 m in size and has walls that are acoustically treated with foam wedges. The anechoic wind tunnel contains an exit cross section that is rectangular and has dimensions of 0.3 m (height) × 0.4 m (span). The flow velocity of the free jet is ranging up to 50 m/s and the free-stream turbulence intensity at the tunnel exit is 0.1 % in terms of the root-mean-square value of the stream wise velocity fluctuation. The test wind tunnel provides a reflection-free environment (ideally) above 100 Hz.

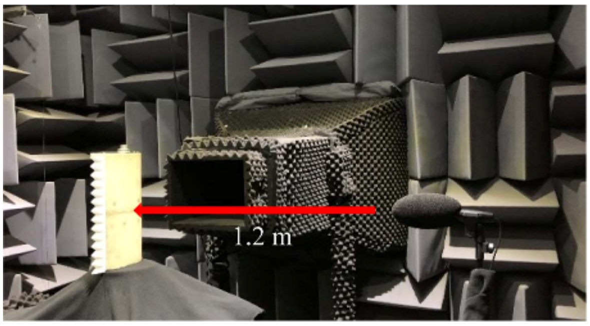


Fig. 1. Pneumatic profile of anechoic wind tunnel.

In our study, the airfoil under investigation was a NACA0018 whose chord c and span s were 0.25 m and 0.45 m, respectively. Between $x/c = 0$ (leading edge) and $x/c = 0.8$ is the original NACA0018 airfoil profile body, where x is the stream-wise direction. From $x/c = 0.8$ to $x/c = 1.0$ is a section that can be removed and replaced by various treated trailing edge serration geometries.

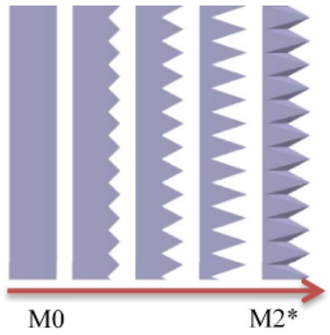
Fig. 2 presents the parameters connected with a non-flat plate trailing edge serration geometry, whose parameters include the serration wavelength λ (tip to tip spanwise distance), the serration length $2h$ (tip to root longitudinal distance), and serration angle φ. Moreover, a significant serration parameter of the non-flat serrate trailing edge, bluntness ε at the root region, is introduced.

Table 1 shows the summary of all trailing edge serration geometrical parameters tested in the present paper according to φ, $2h$, λ, λ / h and ε, in which M0 represents the baseline sharp trailing edge. Serrations M1 to M3 have the same λ but different φ, λ / h and ε, which are called triangular serrations as narrative convenience later. For suppressing the vortex shedding tone noise, a new slanting root serrations M2*, having the same φ, $2h$, λ to M2, is presented, in which a significant slanting root serration parameters describing leaning gratitude, h_1, h_2, are introduced, and $h_2/h_1 = 2$ in this paper.

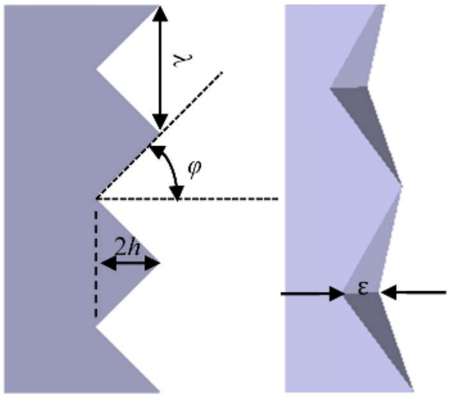
Far field noise measurements in the mid-span were performed by a Hand-held Brüel & Kjær Analyzer Type 2270 including 4189 microphone with a ZE-0032 Microphone Preamplifier shown in Fig. 3, which is installed at a distance of 1.2 m for an observer angle $\theta = 90°$ shown in Fig. 1. The analysis was carried out between 100 Hz and 10 kHz. A mi-

Table 1. Trailing edge serration geometries.

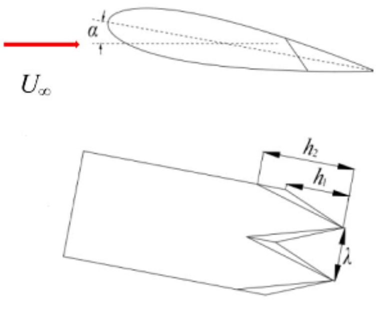
Model	$\varphi(°)$	2 h (mm)	λ (mm)	λ / h	ε(mm)
M0	-	-	-	-	-
M1	45	15	30	4	6.22
M2	28	28	30	2.14	11.22
M3	18	45	30	1.33	17.3
M2*	28	28	30	2.14	/



(a) Straight trailing edge and serrated trailing edges



(b) Serrated geometry parameters



(c) Slanting root serrated trailing edge

Fig. 2. Illustrations of serrated geometry and several nonflat plate-types serrated trailing edges: (a) Straight trailing edge and serrated trailing edges; (b) serrated geometry parameters; (c) slanting root serrated trailing edge.

crophone wind foam protection was applied to the head of the microphone to prevent recirculation flow in the anechoic room to pollute the measurement in the low frequency range.

Fig. 3. Hand-held Brüel & Kjær Analyzer.

3. Results and discussion

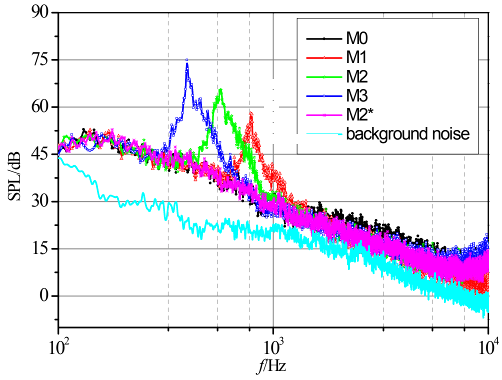
In the present paper, experimental test was made at freestream velocity $U_\infty = 30\ \mathrm{m/s}$. The corresponding to a chord-based Reynolds number is $Re = 5\times10^5$, where kinematic viscosity of air at 20 °C is equal to 15.1×10^{-6}. The angles of attack α vary from 0° to 3° relative to the jet flow direction.

Figs. 4(a) and (b) indicate the comparisons of sound pressure level (SPL) measured, at $U_\infty = 30\mathrm{m/s}$, the angle of attack $\alpha = 0°$, for different serrated trailing edge model and the corresponding ΔSPL, the difference of sound pressure level between serrated trailing edge and baseline trailing edge computed from $\Delta SPL = SPL_{sawtooth} - SPL_{baseline}$, respectively, from which we can see that nonfat plate serrated trailing edge, M1 to M2*, directly cut into the main body of airfoil has substantial effect on the radiated noise spectra compared to the baseline untreated straight trailing edge M0. Moreover, the background noise is less than the airfoil self-noise especially for the low to medium frequency range.

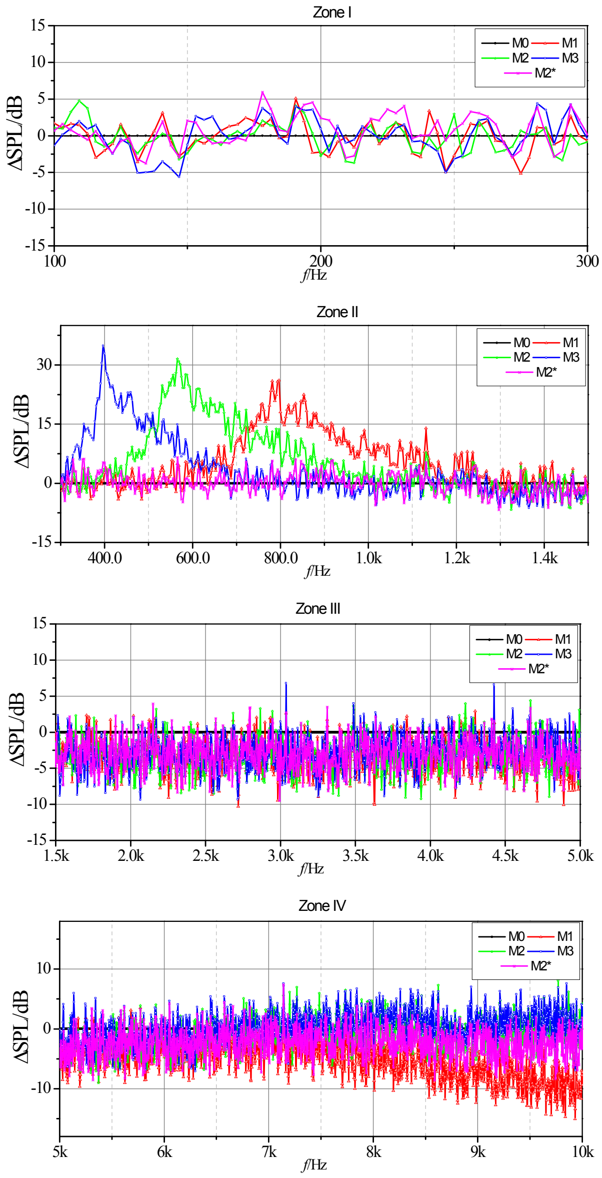
An obvious feature is the large level of narrowband tone noise produced by the blunt part at the root of non-flat plate serrated trailing edge. At frequencies above the shedding frequencies, it was found that noise reduction in the moderate broadband frequency range can be obtained. Moreover, the influence of bluntness tone noise can be eliminated while preserving the broadband noise benefits at other frequencies by using the slanting root serrations configuration.

For a detailed analysis of purpose, the frequency spectra of acoustic were divided into four zones shown in Fig. 4(b), the criterion for the division of which is according to the ΔSPL characteristics.

Zone I presents a low frequency band, i.e., at $f < 300$ Hz, which is just before the occurrence of the vortex shedding tonal noise induced by bluntness at the root of sawtooth, from which we can see that ΔSPL fluctuation in that region about -5.6 dB to 5.9 dB is observed. The overall sound pressure level of the airfoil noise is reduced by a maximum of about 0.24 dB for M1 to M3 type triangular serrations and increases 0.46 dB for slanting root M2* type serrations shown in Table 2. This change at low frequency band is not contributed by the serration effect per se, but the presence of a strong inhomogeneous



(a) Comparisons of SPL



(b) Comparisons of ΔSPL

Fig. 4. Comparisons of (a) SPL measured at $U_\infty = 30\ \text{m/s}$ for baseline sharp trailing edge and nonflat plate serrated trailing edge; (b) the corresponding ΔSPL for frequency zones I, II, III, IV. The angle of attack is set at $\alpha = 0°$.

flow field in the spanwise direction near the serration affecting the efficiency of the jet leading edge interaction noise radiation, the effect of which seems to be less important due to the dominance of jet noise in zone I.

Zone II contains the frequency band at $300\ \text{Hz} < f < 1500\ \text{Hz}$, in which a prominent feature is the tone noise produced by non-flat plate serrated trailing edge. The peak frequencies corresponding to M1-M3 type triangular serrations arise about 784 Hz, 568 Hz and 396 Hz, and the corresponding values are 57.99 dB, 65.51 dB and 74.95 dB, respectively. The peak value of the vortex shedding noise increases when ε increases at the same serration wavelength λ. In other words, the level of the narrowband tone noise is reduced when a large serration angle, φ, is used, which agrees with Chong et al. [17]. It is because of the greater flow mixing near the blunt roots. The large ΔSPL is up to 34.84 dB produced by the non-flat plate M3 type triangular serrations. Such tone noise phenomenon is attributed to the periodic vortex shedding coming from the bluntness at the root of sawtooth when almost no air flow resistivity exists locally for M1 to M3 type triangular serrated trailing edge. Experimental evidence of the periodic vortex shedding can be found in the flow visualization images in Fig. 13 in Chong et al. [14].

When slanting root type serration is inserted into the airfoil trailing edge, this narrowband tone noise ceases to produce in the zone II, which suggests that vortex shedding is now suppressed by the slanting root serrations. In addition, the overall sound pressure level of the airfoil noise increases by a maximum of about 19.52 dB for M1 to M3 type triangular serrations duo to vortex shedding and only 0.61 dB for M2* type slanting root serrations shown in Table 2. But for 3° angle of attack, the overall sound pressure level of the airfoil noise reduces 0.3 dB for M2* type slanting root serrations shown in Table 3.

Zone III contains the frequency band $1500\ \text{Hz} < f < 5000\ \text{Hz}$. Note that the vortex shedding emanating from the root of serrations, being described so far as an unwanted in the frequency zone II, does not seem to deteriorate the serration effect on the broadband frequency noise reduction in zone III. Generally, noise reduction is observed for all cases. The overall sound pressure level of the airfoil noise is reduced by a maximum of about 3.09 dB for all serrations shown in Table 2, from which we can see that it may be impair slightly the noise reduction capability in this frequency zone using M2* type slanting root serrations comparison to M2 type serrations. A similar behavior is obtained for 3° angle of attack shown in Table 3.

Finally, zone IV represents the high frequency band at $5000\ \text{Hz} < f$, in which the trailing edge is unlikely the dominant noise source. Generally, the noise reduction behavior is observed except for M3 type triangular serrations shown in Table 2. But for 3° angle of attack, the overall sound pressure level of the airfoil noise is reduced by a maximum of about 4.35 dB for all cases shown in Table 3. Moreover, it may improve the noise reduction capability in this frequency

Table 2. The overall sound pressure level of the airfoil noise, the angle of attack $\alpha = 0°$.

Frequency band/Hz		M0	M1	M2	M3	M2*
(100-300)	Overall SPL/dB	66.01	65.98	65.82	65.77	66.47
(300-1.5 k)		61.91	69.55	77.48	81.43	62.52
(1.5 k-5 k)		51.57	48.48	48.49	48.61	48.63
(5 k-10 k)		44.01	39.07	43.15	44.33	41.55
(100-10 k)		67.54	71.15	77.77	81.55	67.98

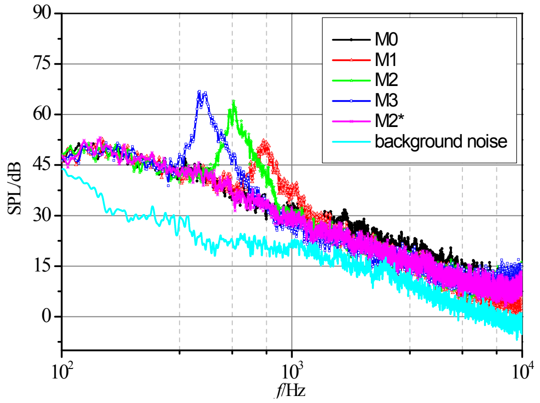
Table 3. The overall sound pressure level of the airfoil noise, the angle of attack $\alpha = 3°$.

Frequency band/Hz		M0	M1	M2	M3	M2*
(100-300)	Overall SPL/dB	65.66	65.84	65.66	65.76	66.08
(300-1.5 k)		62.31	67.75	74.96	78.07	62.01
(1.5 k-5 k)		52.75	49.02	48.54	48.49	49.27
(5 k-10 k)		43.81	39.46	42.27	43.45	41.53
(100-10 k)		67.47	69.94	75.45	78.32	67.58

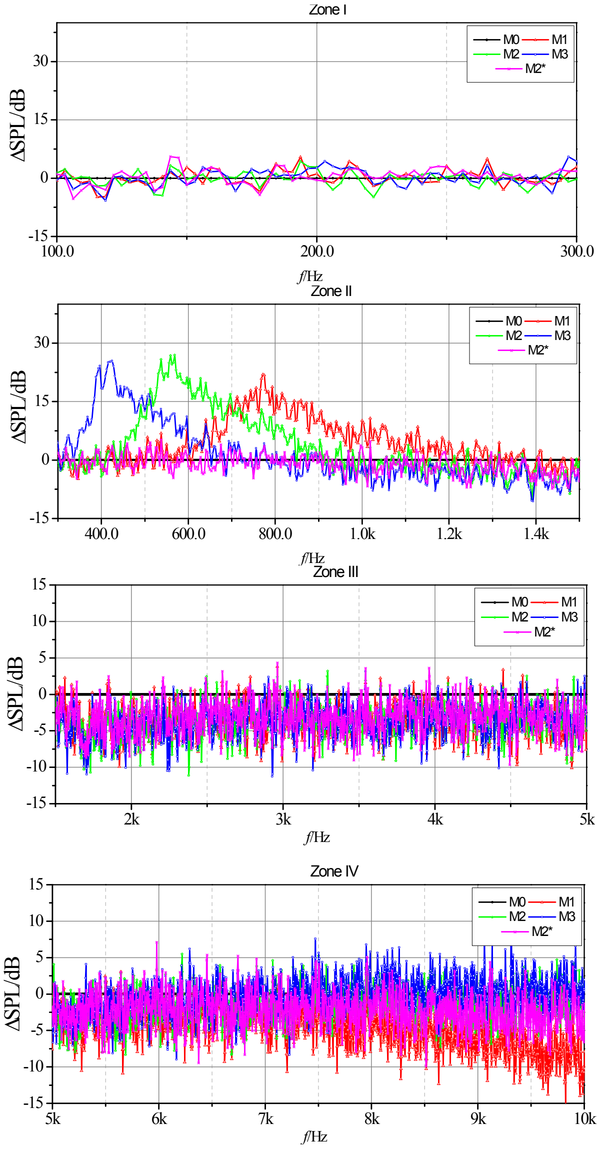
zone using M2* type slanting root serrations comparison to M2 type serrations.

Tables 2 and 3 represent the overall sound pressure level of the airfoil noise for different frequency band corresponding to zone I to zone IV and the angles of attack are set $\alpha = 0°$ and 3°, respectively. As discussed above, for low frequencies $100\text{ Hz} < f < 300\text{ Hz}$, the overall sound pressure level difference between the baseline sharp trailing edge and serrated trailing edge is very slight and noise increase occurs when using slanting root serrations. For frequencies $300\text{ Hz} < f < 1500\text{ Hz}$, the overall sound pressure level increases sharply for M1 to M3 type triangular serrations due to the vortex shedding. The wider the root of sawtooth, the greater is the noise rise at the same serration wavelength λ. However, it is interesting that vortex shedding is now suppressed using the slanting root serrations and noise reductions 0.3 dB for 3° angle of attack. For frequencies $1500\text{ Hz} < f < 10\text{ kHz}$, given the flow conditions of this study, serrated trailing edge is most effective at reducing the radiation efficiency in the frequency range. For the whole frequency range $100\text{ Hz} < f < 10\text{ kHz}$, the overall sound pressure level increases sharply for M1 to M3 type triangular serrations, but increases slightly for slanting root serrations, only is 0.11 dB especially for the angle of attack $\alpha = 3°$. So, it can be deduced that noise reduction can be obtained across the whole frequency range as the angle of attack is further increased using slanting root serrations.

Figs. 5(a) and (b) indicate the comparisons of sound pressure level (SPL) measured, at $U_\infty = 30\text{ m/s}$, the angle of attack $\alpha = 3°$, for different trailing edge model and the corresponding ΔSPL, respectively. A similar behavior is observed as shown in Fig. 4. An obvious feature is that the level of narrowband tone noise is reduced in comparison with that of 0° angle of attack. Multiple-broadband noise reduction mecha-



(a) Comparisons of SPL



(b) Comparisons of ΔSPL

Fig. 5. Comparisons of (a) SPL measured at $U_\infty = 30\text{ m/s}$ for baseline sharp trailing edge and nonflat plate serrated trailing edge; (b) the corresponding ΔSPL for frequency zones I, II, III, IV. The angle of attack is set at $\alpha = 3°$.

nisms can also co-exist in the slanting root serrated trailing edge configuration for 3° angle of attack.

4. Conclusions

This paper presents an experimental study on the aeroacoustic properties of an NACA 0018 with nonflat plate-type trailing edge serration at Reynolds numbers of 500000 in an open-jet wind tunnel. The angle of attack α varies from 0° to 3°. Noise reduction can be obtained in the 1500 Hz-10 kHz frequency range for nonflat plate type triangular serrated trailing edges of airfoil, but at the cost of producing narrowband tone noise attributed to vortex shedding induced at the root of the serration. Our objective was to investigate whether it is feasible that multiple-broadband noise reduction mechanisms can co-exist by employing slanting root serrated trailing edge configuration. Some conclusions as follows.

(1) Noise reduction can be achieved in the moderate frequency range for nonflat plate type triangular serrated trailing edges, but at the cost of producing narrowband tone noise. The level of the narrowband noise is reduced when a large serration angle, φ, is employed. At the same time, a slim, smaller h is also desirable, because it will produce a lower level of the narrowband vortex shedding noise due to the smaller blunt part, the effect of which is in accordance with that of narrower trailing edge serrations employed by Chong [17].

(2) The use of nonflat plate-type slanting root serration can be an effective and versatile strategy to suppress vortex shedding noise; in the meanwhile, the ability of broadband noise reduction is maintained.

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