Experimental Study on Noise Reduction Characteristics of Slanting Serrated Trailing Edge Blades

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Abstract. In order to suppress the narrowband tone noise generated by the blunt part at the root of non-flat plate serrated trailing edge, a novel slanting root serrated trailing edge is adopted on NACA65019 blade. The experimental investigation on the aeroacoustic characteristics of the blade with slanting serrated trailing edge is carried out in the full anechoic wind tunnel laboratory. Reynolds number (Re) based on the chord is 2×10⁵ and attack angle is 0° to 12° in the experiment. The result of experiment shows that the blade with traditional serrated trailing edge will reduce noise in high frequency range at small angle of attack, but it will produce narrow band peaks at specific frequencies, leading to an increase in overall noise level. The blade with slanting serrated trailing edge can maintain the noise reduction effect in broadband frequency range, while significantly weakening narrow band peaks. At the large attack angle, the narrow-band peaks of the traditional blunt trailing edge disappear and the noise reduction effect is obvious, while the novel slanting serrated trailing edge has more obvious noise reduction effect. The results of this paper can pro-vide a new idea for the bionic design configuration of blades.

1. Introduction

Tailing edge self-noise is an important component of blade noise. It is generated by the interaction between the turbulent boundary layer and the trailing edge of the blade[1]. It widely exists in various engineering applications such as fluid machinery, wind turbines and aircraft. Therefore, the research on the mechanism and control of blade trailing edge noise has important theoretical significance and application value.

Scholars at home and abroad have done a lot of research on tail-edge self-noise control. At present, the main noise reduction methods are as follow: serrated trailing edge[2-5], perforation[6-7], brushes[8-9], filling porous media[10]. Because of its low cost and simple shape, the noise reduction of serrated trailing edge has become the most commonly used means in the blade trailing edge self-noise control. In 1991, Howe[11] published the theoretical analysis results of the noise reduction of the serrated trailing edge airfoil imitating the owl wing. He also gave the prediction model of the noise reduction of the serrated trailing edge. The prediction showed that the noise could decrease about 18dB. However, at present, the experimental results of noise reduction by sawtooth trailing edge do not exceed 10dB. There are great differences between theory and experiment which indicates that the mechanism of noise reduction is not clear.
Firstly, it is studied that the sawtooth of thin plate is inserted directly into the trailing edge, without considering the influence of blade shape on noise generation and propagation. It may lead to the change of pressure load on the blade surface. Especially for blades with large curvature, the high adverse pressure gradient on the suction surface will trigger turbulence separation and generate additional noise sources. In addition, it is difficult to maintain the integrity of the structure under high load continuous operation. So, people begin to study how to cut the sawtooth trailing edge directly from the blade to enhance its structural strength, but at the same time, a new problem was introduced. Tong Fan\cite{12} used large eddy simulation and acoustic analogy to study the effect of serrated trailing edge on airfoil self-noise. It is proved that serrated trailing edge can significantly reduce the noise in the middle and low frequency range of airfoil, but at small angle of attack, serrated trailing edge will produce a specific narrow-band spike in a certain frequency range, resulting in the overall level of noise rising. Brooks\cite{13} studied this phenomenon and it was showed that the main reason of narrow-band spike noise is the wake composed of vortex shedding at serrated blunt trailing edge. To weaken the wake shedding, the serrated trailing edge is slanted. The experimental results in a fully anechoic wind tunnel show that the slanting serrated trailing edge can effectively weaken the narrow band peaks.

2. Experimental Method
The experiment was carried out in the laboratory of anechoic wind tunnel of University of Shanghai for Science and Technology. It is an open-jet wind tunnel, which adopts the suction type, as shown in Figure.1. The effective size of the tunnel is about 5.8m x 4.3m x 3.6m. The flow velocity of the free jet is up to 50m/s and the free-stream turbulence intensity at the tunnel exit is 0.2%. The test wind tunnel provides a reflection free environment (ideally) above 100 Hz.

Figure 1 Anechoic wind tunnel laboratory

Figure 2 Noise test-bed

Figure 3 Layout of measurement points

Figure 2 is the diagrammatic sketch of blade noise test bench. The blade length is 420 mm and the chord length is 100 mm. The leading edge of the blade is 500 mm away from the inlet inflow. The
measuring plane is located at 50% of the blade length. In order to reduce the influence of jet boundary, it is necessary to ensure that the measuring surface is located in the jet center as far as possible. The size of the inflow is 0.4m (wide) × 0.3m (high), and the length of the test section is 1.75m. Fig.3 is a diagrammatic sketch of the arrangement of measuring points for acoustic signals on the measuring plane. The measuring point is 1.2m away from the leading edge of the blade. Six measuring points are arranged on both sides of the blade at each 45°.

Measuring instruments use B&K handheld noise analyzer (Type 2270). It uses B&K4189 microphone and ZE-0032 preamplifier. The sensitivity of microphone is 46.0mV/Pa, and the maximum error is less than 0.2dB. A-weighted dynamic range is 16.6~140dB. In order to avoid the reflection of sound reflected by the instrument and the tester, the microphone is connected with the analyzer through the data line. The analyzer is placed on the ground far from the blade and covered with sound absorbing material. The analyzer transmits the collected data to the computer outside the anechoic room through the network wire.

Aiming at the additional noise induced by serrated trailing edge at small inflow angle of attack, the slanting serrated trailing edge is used to control the bluntness of the tooth root. Fig.4 is a sketch of slanting serrated trailing edge blade model of NACA65019 studied in this paper. Its chord length is 100 mm. h and λ represent the height and width of the serrated trailing teeth and φ is the slanting angle of the teeth. Referring to Chong [14] research, this paper chooses λ/c=0.08 and h/c=0.08 to process blade trailing edge. It obtains traditional sawtooth, and then designs the slanting serrated trailing edge. Table 1 is the test model for this article. Model M0 refers to the original NACA65019 straight blade. The φ of M1 is 90° corresponding to traditional serrated trailing edge blades. The φ of M2~M5 is 35°~20°. When the φ is too small, the geometry of the suction surface of the blade will be greatly affected, so the minimum value of the φ in this paper is 20°.

![Figure 4 Sketch map of tilted sawtooth trailing edge](image)

Table 1 Geometric parameters of sawtooth of the trailing edge

| Model | φ       |
|-------|---------|
| M0    | /       |
| M1    | 90°     |
| M2    | 35°     |
| M3    | 30°     |
| M4    | 25°     |
| M5    | 20°     |

3. Measurement Results and Analysis

In this paper, the noise of the model in Table 1 is tested under the conditions at 30m/s (Re=2×10⁵) and different angle of attack (α). The measurement results of 6 points shown in Fig.3 show that the variation of noise spectrum changed with φ is basically the same. Therefore, this paper only analyses the measurement point 1 in Fig. 3.
The main noise was jet noise, which has nothing to do with blades before 300 Hz, so the frequency before 300 Hz was neglected in this paper. Fig. 5 is a comparison between model M0 and background noise when $\alpha=0^\circ$ and $Re=2\times10^5$. The background noise was 49.4 dB and the original blade noise was 58.8 dB. The difference between the two methods is less than 10 dB, so the measurement results need to be corrected according to the principle of sound superposition:

$$L_{p2} = 10\lg(10^{0.1L_{p1}} - 10^{0.1L_{p'}})$$  \hspace{1cm} (1)

$L_{p2}$ is the modified noise characteristic; $L_{p}$ is the measured noise characteristic; $L_{p1}$ is the background noise.

![Figure 5](image)

Figure 5 Contrast between model M0 and background noise($\alpha=0^\circ$, $Re=2\times10^5$)

Fig. 6 shows the distribution of sound pressure of model M0 and M1 with Sr at $u=30$ m/s and $\alpha=0^\circ$, $6^\circ$ $12^\circ$. It shows that model M1 can decrease the sound pressure at 2 kHz~6 kHz when $\alpha=0^\circ$ and $6^\circ$. However, there are obvious “hump” peaks near 1000 Hz frequency, corresponding peaks of 44.43 dB and 41.82 dB. At high angles of attack ($\alpha=12^\circ$), the “hump” gradually disappear. It is consistent with Brooks'[15] theory.

![Figure 6](image)

Figure 6 The noise distribution of the crenation tailing-edge serration

According to the study of TP Chong[16] et al., there are two main reasons for narrow band spikes in airfoils: T-S reflection wave and trailing edge vortex caused by serrated trailing edge.
In order to analyze the reason of the narrow band spikes, the Strouhal number ($St$) is introduced, which is defined as follows:

$$St = \frac{f \varepsilon}{u}$$

Where $\varepsilon$ is the thickness of the serrated trailing edge and $u$ is incoming velocity. $\varepsilon = 3.43 \times 10^{-3}$ m in this paper.

Fig. 7 shows the noise characteristic curves of model M1 at different inflow velocities ($u$) at $\alpha=0^\circ$ and $6^\circ$. It can be seen from the graph that with the increase of inflow velocity, the sound pressure level corresponding to the narrow-band spike increases continuously, but the $St$ corresponding to the spike basically keeps the same. This situation is basically the same as that of TP Chong [16]. Therefore, the slanting trailing edge model is introduced on the basis of M1 to increase the jet resistance at the trailing edge to suppress the narrow-band spikes.
Fig. 8 OASPL ($Re=2 \times 10^5$)

Fig. 8 shows the distribution of the total A-weighted sound pressure level of serrated blades with different slanting angles at different attack while $u=30m/s$. Figure 8 shows that the traditional serrated trailing edge will increase the overall noise level of the blade at small inflow angle of attack ($\alpha=0^\circ$ and $6^\circ$). While $\alpha$ is 12 degree, the total sound pressure level of the blade decreases by 0.24dB. Compared with the traditional serrated trailing edge, the overall noise of the slanting serrated trailing edge is significantly reduced. Compared with the original blade, the noise of model M5 decreases to 0.15dB at $\alpha=0^\circ$. The noise of model M3, M4 and M5 decrease at $\alpha=6^\circ$, and M4 has the best effect, reaching 0.74 dB. The noise of all improved blades decrease at $\alpha=12^\circ$, and M4 has the best effect, reaching 0.98dB. In this paper, it is judged that the serrated blade produces new noise due to the new vortex shedding at the root of the tooth, which causes a "hump" shape narrow band peak in the intermediate frequency range, leading to an increase in the total sound pressure level. But the slanting serrated trailing edge makes the trailing edge sawtooth smoother and eliminates the generation of new vortex shedding.
In order to analyze the influence of sawtooth slanting angle on the spectral characteristics of blade noise, the sound pressure level distribution of each model at measuring point 1 is compared and analyzed under the condition of \( Re=2\times10^5 \), as shown in Fig.9. Fig. 9 (a) shows the noise spectrum distribution of each blade model at \( \alpha=0^\circ \). It can be seen from the figure that the traditional serrated trailing edge has noise reduction effect in the range of 2 kHz~6 kHz, but it will produce a narrow band peak around 1 kHz, which will lead to the increase of the total sound pressure level of the blade. With the decrease of the \( \phi \), the range of sound pressure higher than \( M_0 \) is basically unchanged, but the peak value decreases continuously. The peak value disappears when \( \phi=30^\circ \). It can be seen from the graph that the slanting serrated trailing edge can guarantee the noise reduction effect of the serrated trailing edge in the high frequency range, and weaken the narrow band peaks brought by the serrated trailing edge. The smaller \( \phi \) is, the better the effect is. Fig. 9 (b) and (c) show the noise spectrum characteristics of each model at \( \alpha=6^\circ \) and \( \alpha=12^\circ \). When the angle of inclination is \( 6^\circ \), the effect of slanting angle is basically consistent with that of \( \alpha=6^\circ \). When \( \alpha=12^\circ \), the noise distribution of the slanting serrated trailing edge is basically the same as that of the original blade, but slightly lower than that of the traditional serrated trailing edge. Figure 9 shows that the slanting serrated trailing edge has better noise reduction effect than the traditional serrated trailing edge, and the smaller the value of the more significant the noise reduction effect.

In order to analyze the effect of noise reduction in different frequency bands better, the frequency bands are divided into three parts according to the frequency of narrowband peak: 300 Hz to 700 Hz, 700 Hz to 1.5 kHz and 1.5 kHz to 10 kHz. Table 2, 3 and 4 give the overall sound pressure level of different blade models in each frequency band when \( \alpha=0^\circ, 6^\circ \) and \( 12^\circ \). For the noise in the frequency range of 300 Hz to 700 Hz, the blades of each model have the effect of noise reduction. The larger attack angle is, the more obvious the effect of noise reduction is. When \( \alpha=0^\circ \), \( M_1 \) has the best effect of noise reduction.
reduction, which reaches to 0.24 dB; When $\alpha=6^\circ$, M4 has the best effect of noise reduction, which reaches to 0.91 dB; When $\alpha=12^\circ$, M4 has the best effect of noise reduction, which reaches to 1.37 dB. For the frequency range (700 Hz~1.5 kHz) near the peak, the sound pressure level of model M1 is significantly higher than that of M0 at $\alpha=0^\circ$ and $6^\circ$, and M2~M5 can effectively suppress the increase of sound pressure level. M3 has the effect of noise reduction when $\alpha=6^\circ$. When $\alpha=12^\circ$, the noise of M1 does not significantly increase like small attack angle, but it is higher than that of the noise of the M2~M5. For the high frequency band (1.5 kHz~10 kHz), when $\alpha=0^\circ$ and $6^\circ$, each model has the effect of noise reduction. When $\alpha=12^\circ$, the noise of M1~M5 is higher than that of M0, and M1 is the most obvious.

| Table 2  | The overall sound pressure level of the airfoil noise($\alpha=0^\circ$) |
|----------|---------------------------------------------------------------|
| OASPL/dB | M0   | M1   | M2   | M3   | M4   | M5   |
| 300~700 Hz | 60.40 | 60.16 | 60.72 | 60.62 | 60.79 | 60.24 |
| 700~1.5k Hz | 55.58 | 61.37 | 58.66 | 56.73 | 56.09 | 55.71 |
| 1.5k~10k Hz | 47.21 | 46.32 | 44.05 | 44.50 | 44.80 | 44.90 |

| Table 3  | The overall sound pressure level of the airfoil noise($\alpha=6^\circ$) |
|----------|---------------------------------------------------------------|
| OASPL/dB | M0   | M1   | M2   | M3   | M4   | M5   |
| 300~700 Hz | 60.58 | 59.78 | 59.73 | 59.94 | 59.67 | 60.13 |
| 700~1.5k Hz | 55.09 | 59.25 | 57.92 | 56.55 | 55.26 | 55.01 |
| 1.5k~10k Hz | 47.69 | 44.91 | 46.92 | 43.95 | 43.48 | 43.99 |

| Table 4  | The overall sound pressure level of the airfoil noise($\alpha=12^\circ$) |
|----------|---------------------------------------------------------------|
| OASPL/dB | M0   | M1   | M2   | M3   | M4   | M5   |
| 300~700 Hz | 61.40 | 60.50 | 60.42 | 60.36 | 60.03 | 60.59 |
| 700~1.5k Hz | 54.08 | 55.96 | 54.48 | 54.54 | 54.53 | 54.84 |
| 1.5k~10k Hz | 46.36 | 48.62 | 46.81 | 46.48 | 46.97 | 46.97 |

4. Conclusion
Aiming at the "hump" shaped narrow-band peaks caused by traditional serrated trailing edge, the slanting serrated trailing edge is adopted. Noise measurement is carried out in the anechoic wind tunnel to study the influence of slanting serrated trailing edge airfoil on noise spectrum. The following rules are obtained:

1) The traditional sawtooth blade with serrated trailing edge produces an obvious "hump" shape peak near a certain frequency range at a small angle of attack, which leads to the increase of the total sound pressure level of the blade. It considers that there is almost no airflow resistance at the trailing edge of serrated trailing edge blades, and the bluntness of the sawtooth root causes periodic vortex shedding, which leads to the generation of narrow-band peaks.

2) In the small angle of attack, slanting serrated trailing edge can reduce the narrow-band peak caused by blunt trailing edge, and the smaller the angle is, the better the effect is. The peak value disappears when $\phi=30^\circ$. At the same time, the slanting serrated trailing edge can ensure the noise reduction effect of the traditional serrated trailing edge in the high frequency range. The slanting serrated trailing edge weak the narrow-band peak, because it increases the jet resistance at the trailing edge. The smaller the $\phi$ is, the more unfavorable the vortices at the trailing edge is and the better the effect of weakening the peaks is.
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