Effects of Sinusoidal Serrated Trailing Edges on the Wake and Aerodynamic Performance of an Axial Flow Fan Postprint

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Abstract

Trailing edge vortex shedding in axial flow fans constitutes a significant factor in noise generation. To improve wake flow characteristics and reduce fan noise, a sinusoidal serration structure was implemented at the trailing edge of an axial flow fan, and its influence on the fan' s wake flow and aerodynamic performance was analyzed through steady and unsteady numerical simulations combined with experimental validation. The results demonstrate that the sinusoidal serration structure attenuates the work capacity of the blade trailing edge, leading to a reduction in fan total pressure, yet enhances fan efficiency under small and medium flow rate conditions. Furthermore, the structure reduces wake intensity below the mid-span region of the blade, with its inhibitory effect on the wake gradually diminishing from the blade root toward the mid-span. By compensating for the pressure loss induced by the serration structure through increased rotational speed, numerical noise prediction analysis was performed on both the prototype fan and the serrated trailing-edge fan at the design flow point. The results reveal significant improvement in low-frequency noise compared to the prototype, indicating that this trailing-edge sinusoidal serration structure represents, to a certain degree, an effective approach for suppressing low-frequency noise in axial flow fans.

Full Text

The Influence of Sinusoidal Serrated Trailing Edge on the Wake and Aerodynamic Performance of Axial Fan

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Abstract

Vortex shedding at the trailing edge of axial fans constitutes a significant noise source. To reduce fan noise by improving wake flow characteristics, this study investigates the effects of a sinusoidal serrated structure added to the trailing edge of an axial fan on wake behavior and aerodynamic performance through steady and unsteady numerical simulations combined with experimental validation. The results demonstrate that the sinusoidal serrated structure weakens the work capacity at the blade trailing edge, thereby reducing the total pressure of the fan while enhancing efficiency under small and medium flow rate conditions. The structure effectively attenuates wake intensity below the mid-span region of the blade, with the inhibitory effect gradually diminishing from the blade root toward the mid-span. To compensate for the pressure loss induced by the serrated structure, noise numerical predictions were conducted for both the prototype fan and the serrated trailing edge fan at elevated rotational speed. The results reveal significant improvement in low-frequency noise compared with the prototype, indicating that this sinusoidal serrated trailing edge structure represents an effective approach for suppressing low-frequency noise in axial fans.

Keywords: sinusoidal serrated trailing edge; axial fan; wake; noise

1 Prototype Fan Model and Serrated Structure Parameters

The selected axial fan features no inlet or outlet guide vanes and employs straight blades. The impeller structure is shown in [Figure 1: see original paper], with the following geometric parameters: impeller outer diameter $D = 900$ mm, blade number $Z = 9$, hub ratio $d_h = 0.226$, and root installation angle $\beta_A = 35°$. At the design operating point, the flow rate is $Q = 8.4$ m^3/s, total pressure $P_{tf} = 340$ Pa, and rotational speed $n = 1460$ r/min.

The serrated structure was created by removing material from the trailing edge of the prototype fan impeller. A sinusoidal serration shape was adopted, with the tooth tips falling on the original blade trailing edge. The serration width is $\lambda = 9.2$ mm and height $h = 4.6$ mm, yielding an aspect ratio of $\lambda/h = 2$. Twenty-six serrations were uniformly distributed along the trailing edge, with the first serration starting at 13.5% span and the last terminating at 84.1% span. For convenience, the prototype fan is designated as Model A, and the fan with serrated trailing edge as Model B. The impeller model with serrated trailing edge and detailed dimensions are illustrated in [Figure 2: see original paper].

Axial fans are widely employed in various applications, and noise reduction represents a primary research focus. Vortex shedding from blade trailing edges constitutes a major noise source, and improving flow characteristics at the trailing edge can effectively reduce fan noise. Wake control serves as an effective noise reduction strategy, with methods including trailing edge perforation, trailing edge slots, trailing edge blowing, and trailing edge serrations [1]. Considering structural constraints in low-pressure axial fans, trailing edge serrations offer a simple and practical wake control approach.

Howe [2,3] theoretically investigated the noise reduction potential of sinusoidal and triangular serrated trailing edges, demonstrating that properly designed serrated structures can significantly reduce trailing edge noise within specific frequency ranges, thereby establishing the theoretical foundation for serrated structure applications. You Bin [4] applied trailing edge serrations to an axial fan impeller in an outdoor air conditioning unit, showing that the serrated structure can weaken the downstream wake and reduce noise. Gong Wuqi [5] experimentally demonstrated that serrated structures achieve optimal noise reduction when the serration dimensions approximate the wake width in outdoor air conditioning unit axial fans. Liu Xiaomin [6] applied bionically designed trailing edge serrations to a multi-blade centrifugal fan, also achieving noise improvement.

Previous research on the effects of serrated structures on fan noise has primarily focused on small-scale fans and outdoor air conditioning unit axial fans, with limited application in industrial ventilation fans. This study investigates the influence of sinusoidal trailing edge serrations on the wake and aerodynamic characteristics of an axial flow fan.

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2 Numerical Methods

2.1 Numerical Methodology

The computational domain employed a pressure inlet boundary condition at the inlet and pressure outlet at the exit. For steady-state solutions, the Reynolds-averaged Navier-Stokes (RANS) equations were solved using the Realizable k-ε turbulence model. The SIMPLE algorithm was employed for velocity-pressure coupling, with second-order discretization schemes. Convergence was considered achieved when residuals fell below 1×10^{-5} and monitored values stabilized.

2.2 Grid Generation and Independence Verification

The computational domain was divided into inlet, impeller, and outlet regions. Structured hexahedral grids were used for the inlet and outlet domains, while unstructured tetrahedral grids were employed for the impeller domain. Given the relatively small serration dimensions compared to the impeller, local grid refinement was applied to the trailing edge region where serrations were present. [Figure 3: see original paper] presents the overall computational model for Model B, the impeller domain grid, and the detailed mesh at the serrated trailing edge.

Numerical results are influenced by grid density. To ensure grid independence, a grid independence test was conducted for Model A. As shown in [Figure 4: see original paper], when the total grid number exceeded 8×10^6, both fan torque and efficiency remained essentially unchanged with further grid refinement. For Model A, the inlet domain contained 1,089,616 cells, the impeller domain 9,057,815 cells, and the outlet domain 868,521 cells, totaling 11,015,952 cells. After adding the trailing edge serrations, the blade trailing edge geometry changed slightly. While maintaining identical grid sizes in the same regions, the impeller domain cell count differed between models, but both total grid counts exceeded 8×10^6, ensuring negligible grid dependence.

2.3 Aerodynamic Characteristics Simulation and Experimental Comparison

To validate the numerical simulation accuracy, aerodynamic performance tests were conducted on Model A using an experimental facility conforming to GB/T1236-2000 standards, configured as a Type C test device as shown in [Figure 5: see original paper]. [Figure 6: see original paper] compares the simulated and experimental performance curves for Model A, showing consistent trends in total pressure and efficiency variation with flow rate. The maximum total pressure error was 4.58% and the maximum efficiency error was 3.97% at equivalent flow rates, confirming the credibility of the simulation methodology.

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3 Results and Analysis

3.1 Influence on Work Capacity

[Figure 7: see original paper] compares the aerodynamic performance of Models A and B at identical rotational speeds. With the serrated trailing edge, the total pressure decreased across the entire flow range, while efficiency improved by 1-2% under small and medium flow conditions. At the design flow point ($Q = 8.4$ m³/s), the total pressure decreased by 11.5% while efficiency remained unchanged.

To further investigate the influence of the trailing edge serration structure on fan work capacity, the internal flow fields of Models A and B were compared at the design flow point. [Figure 8: see original paper] presents the blade surface static pressure distributions at 25%, 50%, and 75% spanwise positions. At all three spanwise locations, the static pressure distributions near the leading edge remained essentially identical between the two models. However, from the mid-chord to trailing edge region, Model B exhibited lower static pressure on the pressure surface and higher static pressure on the suction surface compared to Model A. This indicates that the trailing edge serration structure does not affect the work capacity near the leading edge but primarily acts on the mid-to-rear portion of the blade near the trailing edge, reducing pressure surface pressure and increasing suction surface pressure. This diminishes the work capacity of the trailing edge region, resulting in decreased total pressure.

3.2 Velocity Distribution in Trailing Edge Region

Three circular lines were extracted at axial positions 3 mm downstream of the blade trailing edge at 25%, 50%, and 75% spanwise positions for Model A. Corresponding axial velocities were extracted at identical locations for Model B. [Figure 9: see original paper] shows the circumferential distribution of axial velocity at these three circular positions for both models.

The local minima of axial velocity in the circumferential direction correspond to the wake center velocity. The wake center velocity coefficient is defined as $\varphi_c = Cz_{\min}/Cz$, where $Cz = \oint Cz\,dl/\oint dl$ represents the circumferential average of axial velocity. A smaller φ_c value indicates a larger difference between wake center velocity and mainstream velocity, signifying a stronger wake. Conversely, a larger φ_c value indicates a weaker wake. Variations in φ_c along the axial direction thus reflect wake evolution.

[Figure 10: see original paper] presents the streamwise variation of φ_c at 25%, 50%, and 75% spanwise positions, where the horizontal axis represents the flow direction (0 denotes impeller inlet, 1 denotes impeller exit). The coefficient φ_c increases rapidly to its maximum value and then decreases gradually. Before reaching maximum φ_c, the serrated trailing edge yields larger φ_c values at identical axial positions, indicating wake velocities closer to the mainstream and thus weaker wakes. Furthermore, at the 50% spanwise cylindrical surface, the serrated configuration reaches its maximum φ_c over a shorter circumferential distance. This suggests that while serrations reduce wake intensity, they may also accelerate local wake decay.

3.3 Pressure Fluctuation in Trailing Edge Region

Based on steady-state calculations, Large Eddy Simulation (LES) was performed using a sliding mesh model for the impeller domain. The PRESTO! scheme was employed for pressure discretization, bounded central differencing for momentum, and bounded second-order implicit formulation for temporal terms. The time step corresponded to the duration for 1° of impeller rotation.

Three monitoring points were established on circumferential cylindrical surfaces at 25%, 50%, and 75% spanwise positions, located 3 mm axially downstream from the intersection of the blade trailing edge with these surfaces. [Figure 11: see original paper] shows the temporal pressure fluctuations at these monitoring points over one period, with the horizontal axis representing the period number and the vertical axis representing static pressure. Both Models A and B exhibit regular pressure variations with time, showing nine peaks and troughs corresponding to the nine blades. Pressure fluctuations become more intense with increasing spanwise height, while Model B consistently shows smaller pressure variation amplitudes than Model A at identical spanwise positions.

When frequency exceeds 1000 Hz, pressure fluctuation amplitudes become negligible. [Figure 12: see original paper] therefore presents pressure fluctuations within five times the blade passing frequency (with nine blades at 1460 r/min, the rotational fundamental frequency is 219 Hz). The figure shows that pressure fluctuation amplitudes at the fundamental and second harmonic frequencies are significantly larger than at other frequencies. At identical monitoring locations, the serrated fan exhibits substantially reduced pressure amplitudes at the fundamental and second harmonic frequencies, with reductions of 30.0% at the fundamental frequency and 58.2% at the second harmonic frequency at the 25% span position. This indicates that the pressure fluctuation reduction induced by the trailing edge serration structure primarily occurs in the low-frequency range, including the fundamental and second harmonic frequencies.

The dipole noise source term in the acoustic wave equation [7,8] is expressed as:

$$r(y,\tau) = -\frac{x_i - y_i}{rc_0}\Delta s_i \frac{\partial p}{\partial t}$$

Analysis reveals that aerodynamic noise at far-field locations is primarily determined by the time variation of the pressure fluctuation term $\Delta s_i \partial p/\partial t$, which is orders of magnitude larger than the other terms and constitutes the dominant factor determining sound source intensity. Consequently, the reduction in pressure fluctuation at the trailing edge leads to decreased sound source strength.

3.4 Aerodynamic Noise Prediction and Analysis

The serrated structure reduces the work capacity of the fan, resulting in partial aerodynamic performance loss. This can be compensated by increasing the rotational speed. The rotational speed was therefore increased from 1460 r/min to 1510 r/min, with the resulting configuration designated as Model C. As shown in [Figure 13: see original paper], Model C' s pressure curve essentially matches that of Model A, while fan efficiency improves by approximately 2% across the entire flow range.

Noise analysis was performed on Models A and C at the design flow point. A two-step approach was employed: first, LES unsteady calculations were conducted to obtain source information until the monitored impeller torque exhibited stable periodic variation, indicating convergence. The Ffowcs Williams-Hawkings (FW-H) equation was then applied to integrate the source information and obtain acoustic signals at monitoring points, which were subsequently transformed via FFT to acquire frequency-domain noise characteristics.

Fan noise measurements were conducted at the measurement point indicated in [Figure 5: see original paper]. presents both predicted and measured values for Models A and C at this location. The predicted and measured values for

Model A differ by 3.3 dB, representing a 3.6% error. Considering the complex field environment and simulation simplifications, the numerical results are considered credible. At this noise measurement point, Model C exhibits a 0.9 dB lower sound pressure level than Model A, confirming that the serrated structure effectively reduces fan noise.

[Figure 14: see original paper] shows the 1/3-octave A-weighted sound pressure level spectrum at the measurement point. In the low-frequency range below 256 Hz, Model C demonstrates substantial noise reduction. In the mid-to-high frequency range, the reduction is less pronounced, while slight increases occur in narrow bands near 512 Hz and 3000 Hz. This indicates that the sinusoidal trailing edge serration structure suppresses low-frequency noise, consistent with the low-frequency pressure fluctuation attenuation observed in [Figure 12: see original paper].

Conclusions

Through steady and unsteady numerical simulations combined with experimental validation, this study investigated the influence of sinusoidal trailing edge serrations on the wake and aerodynamic characteristics of an axial flow fan, yielding the following conclusions:

1. The sinusoidal trailing edge serration structure reduces the work capacity at the blade trailing edge, decreasing total pressure while improving fan efficiency.
2. The structure attenuates wake intensity from the blade root to mid-span, with the inhibitory effect gradually diminishing from the root toward the mid-span. Additionally, it helps reduce pressure fluctuations in the wake region, primarily affecting low-frequency components including the fundamental and second harmonic frequencies.
3. After compensating for the pressure loss induced by the serration structure through increased rotational speed, the fan achieves both improved efficiency and noise reduction, with primary suppression of low-frequency noise.

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Note: Figure translations are in progress. See original paper for figures.