

Geometry Effect of Streamwise Finlet on Manipulating Wall-Pressure Fluctuations

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ABSTRACT

This study examines how streamwise finlet geometry manipulates turbulent boundary-layer structures to attenuate wall-pressure fluctuations and reduce trailing-edge noise with a limited drag penalty. Three finlet configurations mounted on a NACA0018 airfoil are compared by separately modifying the leading-edge and rear profiles. Flow-field measurements show that all finlets disrupt the original near-wall streaky structures and redistribute vortical structures within the boundary layer, which reduces wall-pressure fluctuations and yields similar far-field noise reduction. The different drag penalties among the three configurations further indicate that finlet shape can be optimized to reduce drag while preserving the acoustic benefit. The leading-edge profile changes the interaction between the incoming flow and the finlets, thereby modifying the onset and wall-normal position of the detached shear layer. A more gradual leading edge reduces the velocity deficit and drag penalty, but places the shear layer closer to the wall, which slightly weakens the wall-pressure fluctuation and noise reduction. The rear profile mainly affects local low-speed and reverse-flow events near the finlet rear. A smoother rear profile suppresses these near-wall events and reduces the high-frequency velocity fluctuations, leading to a lower drag increase.

1. Introduction

Finlet treatment is a useful biomimetic approach proposed by Clark et al. (2016) for mitigating the trailing edge noise, which is one of the dominant noise sources of aircraft, wind turbines, and marine propellers (Lee et al., 2021), caused by the interaction between the turbulent boundary layer and the sharp trailing edge of the airfoil (Brooks, Pope, & Marcolini, 1989). Inspired by fine downy filaments over the wings of the owl, by applying a spanwise array of thin and elongated finlets close to the trailing edge, Clark et al. successfully achieved up to 10 dB of broadband noise attenuation. The reduction of wall-pressure fluctuations in mid- and high-frequency ranges is found to be one of the key causes for reducing trailing-edge noise. They argued that the mechanisms lie in modifying the boundary layer properties and flow structures, rather than affecting the noise scattering efficiency.

Following this, an increasing number of researchers have conducted more in-depth investigations into the noise reduction mechanisms of finlets (Ananthan & Akkermans, 2023; Fiscaletti, Luesutthiviboon, Avallone, & Casalino, 2022; Millican, Clark, Devenport, & Alexander, 2017; Shi & Kollmann, 2021; Shi & Lee, 2020). Bodling and Sharma (2019), by performing wall-resolved large eddy simulation with finlets applied at the trailing edge of a NACA0012 airfoil, found that finlets can attenuate turbulent kinetic energy in the near-wall region, while elevated turbulence levels appear above the finlets. Additionally, Afshari et al. (2019), using hot-wire point measurement on a flat plate, proposed that the increase of energy dissipation through surface friction of the finlet walls leads to the reduction of the wall-pressure fluctuation in the mid- and high-frequency ranges, and the increase in the low-frequency range is due to a separated shear layer developed downstream of the finlets. Gstrein et al. (2023) extended the experimental work of Afshari et al. and proposed that the mixing and merging of turbulent structures shed above the finlets with the channeled turbulent flow through them can significantly enhance viscous friction. As a result, near-wall turbulent intensity and pressure fluctuations are attenuated. Pan and Ye (2025) conducted a comprehensive experimental investigation employing time-resolved particle image velocimetry, wall-pressure transducers, and far-field acoustic measurements on a NACA0018 airfoil. By directly observing the flow structures, they indicate that the finlets effectively break down the flow structures and give rise to newly hairpin-shaped vortices above the finlets and spanwise rollers close to the rear of the finlet. In addition, an overall lift-up process shifts the most energetic fluctuations away from the wall and consequently lowers the wall-pressure fluctuations.

Beyond the investigation of noise reduction mechanisms, considerable efforts have also been devoted to parametric studies aimed at optimizing the noise attenuation performance of finlets while minimizing their impact on aerodynamic characteristics (I. A. Clark et al., 2017; Gstrein, Zang, Mayer, & Azarpeyvand, 2021; Kim, Scholz, Chong, Joseph, & Vronsky, 2022). Among these parameters, finlet spacing and height have received the most extensive attention (Afshari et al., 2019; Pan & Ye, 2025). However, finlet geometry, as another key parameter, has not yet been deeply explored. In the existing research, the finlet shapes employed are predominantly based on the original configuration proposed by Clark et al. (2016) and the subsequent designs introduced by Afshari et al. (2019). In the numerical simulations conducted by Bodling et al. (2019), it was found that rectangular finlets, compared to conventional finlets, are also capable of reducing turbulent kinetic energy in the near-wall region. However, due to enhanced interactions between the finlets and the incoming flow, stronger turbulent kinetic energy is generated above the finlets. Gstrein et al. (2023), through hot-wire point measurements and wall-pressure fluctuation measurements, observed that although rectangular finlets can attenuate pressure fluctuations in

the wake region similarly to conventional finlets, they induce stronger pressure fluctuations near the leading edge. Furthermore, the noise reduction performance of rectangular finlets is significantly diminished. Using Reynolds-averaged Navier-Stokes simulation and an artificial neural network-based surrogate model and genetic algorithm, Luo et al. (2020) summarized the optimal finlet height, spacing, and geometry that achieve the best noise reduction performance while balancing aerodynamic characteristics. However, they did not provide a mechanistic understanding of the underlying processes and trends.

The present investigation focuses on how streamwise finlets modify boundary-layer turbulent structures and the associated wall-pressure fluctuations, aiming to achieve trailing-edge noise reduction with a limited drag penalty. By separately modifying the leading-edge and rear profiles, the roles of different geometric portions of the finlet are clarified. Far-field noise and aerodynamic drag are first measured using a microphone array and a wake rake, respectively, to evaluate the noise-reduction performance and drag penalty. The wall-pressure fluctuations are then captured using an array of pressure transducers, and time-resolved planar and tomographic PIV measurements are used to identify the corresponding flow-field response, including the redistribution of near-wall turbulent structures, the formation of the detached shear layer, and local unsteady events near the finlet rear. This combined analysis provides a basis for understanding how finlet geometry can maintain effective noise reduction while reducing the associated drag penalty.

2. Experimental setup and test facilities

2.1 Flow facility and finlet configurations

The experiments were performed in an open-jet low-speed anechoic wind tunnel at the Institute of Fluid Engineering, Zhejiang University. The test section dimensions are 500 mm in width and 400 mm in height. A maximum incoming velocity of 60 m/s could be achieved, with the turbulent intensity maintained below 0.5%. As illustrated in Fig.1(a), an aluminum NACA0018 airfoil was used in this experiment, possessing a chord length (c) of 200 mm and a span (l) of 400 mm. Tests were conducted at a freestream velocity (U_∞) of 15 m/s, corresponding to a chord-based Reynolds number ($Re_c = \rho U_\infty c / \mu$) of 2.0×10^5 , with the airfoil fixed at a 0° geometric angle of attack. To ensure a fully developed turbulent condition upstream of the finlet region, a zig-zag trip with a thickness of 0.8 mm and a width of 9 mm was positioned 8 mm downstream of the leading edge. Thin substrates were often used to install finlets on the airfoil in previous studies (Afshari et al., 2019; Gstrein et al., 2023; Pan & Ye, 2025), which may intensify local adverse pressure gradients and promote the formation of turbulent structures. To avoid the impact of the substrate on the

flow field and aerodynamic performance of the airfoil, following Clark et al. (2016), a shallow pocket with a depth of 0.5 mm and length of 50 mm was cut into the suction and pressure side surface, as shown in Fig.1(b), in which the substrate could fit flush. A narrow ridge with a width of 2.5 mm is kept for measuring wall-pressure fluctuations, which will be discussed in more detail in the following text.

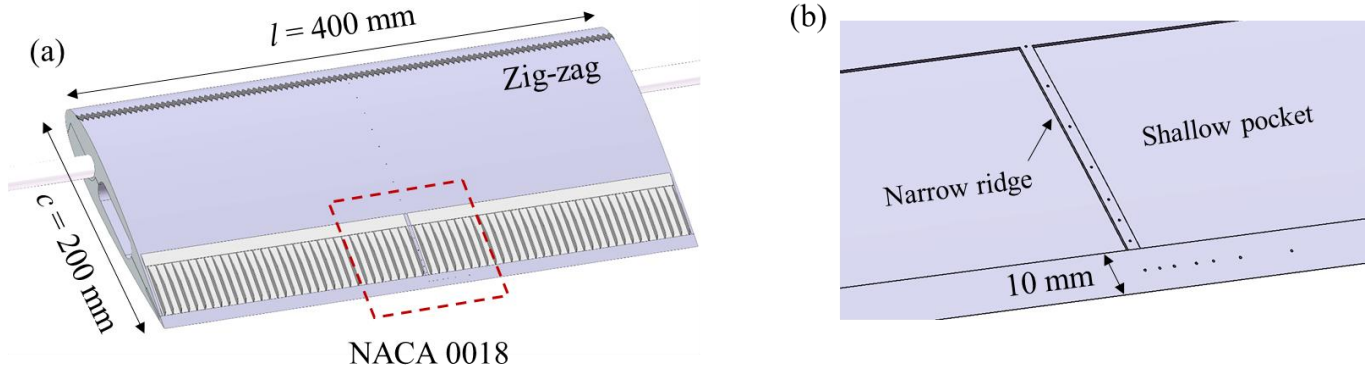


Fig.1 Conceptual sketch of model and experiment set-up: (a) NACA0018 airfoil with finlet treatment; (b) pocket design on airfoil.

The finlet treatments, as shown in Fig.2, are manufactured by 3D printing using resin, consisting of a series of vertical finlets oriented in the streamwise direction with a thickness of 0.5 mm. The conventional finlet design follows the configuration proposed by Afshari et al. (2019), as illustrated in Fig.2(a), and is referred to as type A. The length (L), spacing (S), and height (H) of the finlets used in this experiment are 40 mm, 3 mm, and 4 mm, respectively. A local Cartesian coordinate is introduced with the origin (O_F) located at the front of the finlets, where the x_F -axis is parallel to the finlets, and the y_F -axis is perpendicular to the substrate plane. Each finlet consists of a gently sloped leading-edge section, a flat plateau section, and an arc-shaped trailing-edge section, as shown in Fig.2(a). Compared to the finlets of type A, the type B eliminates the plateau section, as shown in Fig.2(b), resulting in a more gradual slope of the leading-edge section. In addition, the type C finlet, as shown in Fig.2(c), features a shortened plateau section. The trailing-edge section is transformed from a circular arc into a straight ramp, allowing for a smoother transition between the finlet and the surrounding flow. The transition between the plateau section and the sloped trailing-edge section is achieved through a fillet with a radius of $2H$.

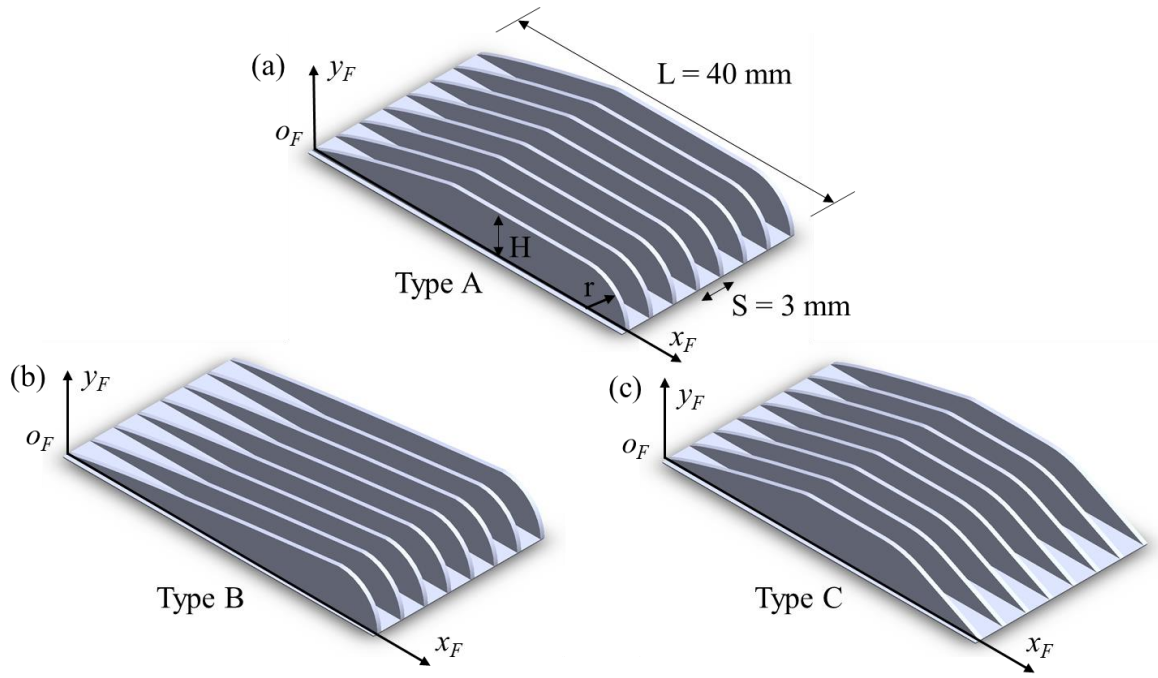


Fig.2 Finlet design and geometric parameters: (a) type A; (b) type B; (c) type C.

2.2 Far-field noise measurement

Far-field acoustic measurements were conducted using a beamforming microphone array consisting of 64 GRAS 40PH-10 CCP free-field microphones. The microphones have a frequency response of $\pm 2\text{dB}$, working in a frequency range from 10 Hz to 20 kHz with a maximum output of 135dB ref. $20\mu\text{Pa}$. The array was mounted at a distance of 1m from the spanwise centre of the airfoil trailing edge, as shown in Fig.3. The acoustic signals were acquired using a National Instruments PXIe-4499 at a sampling frequency of 50 kHz for a duration of 30 s. The measured time series were processed using a Hanning window with 50% overlap and a block size of 4096 samples. The far-field noise was then evaluated in 1/3-octave frequency bands using the delay-and-sum beamforming algorithm implemented in the Acoular software package.

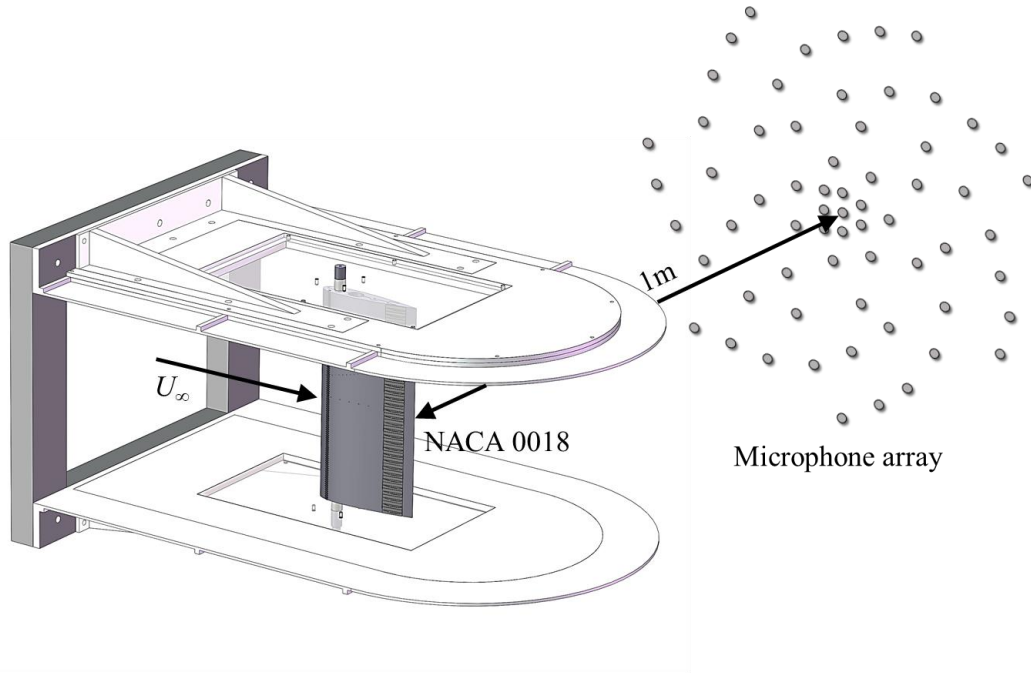


Fig.3 Schematic of the far-field noise measurement set-up.

2.3 Drag coefficient measurement

The aerodynamic drag was evaluated from wake survey measurements performed using a traversing wake rake downstream of the airfoil. The wake rake was positioned $1.5c$ downstream of the airfoil trailing edge and was used to measure the momentum deficit, from which the drag coefficient was determined. The wake rake consisted of 29 total-pressure tubes and 2 static-pressure tubes. The wake centerline was aligned with the trailing edge so that the momentum-deficit region was fully captured within the rake span. This method was applied to compare the aerodynamic penalty induced by different finlet geometries.

2.4 Unsteady wall-pressure fluctuation measurement

Unsteady wall-pressure fluctuations (p') were measured using FG-23329-P07 pressure transducers using a remote microphone probe technique (Maryami, Arcondoulis, & Liu, 2024; Vemuri, Liu, Zang, & Azarpeyvand, 2020). This configuration provides higher spatial resolution for wall-pressure measurements. Each microphone was mounted outside the test model and connected to a 0.4 mm diameter pinhole on the airfoil surface via a 400 mm long plastic tube with an internal diameter of 1 mm. As shown in Fig.4, eight pressure transducers were installed along the spanwise symmetry plane ($z = 0$ mm). An additional seven transducers were distributed along the span at $x = -5$ mm, corresponding to 97.5% chord length. This arrangement captures the streamwise development of wall-pressure fluctuations between finlets. All pressure transducers

were calibrated against a GRAS 40PH-10 CCP reference microphone, following the procedure described by Botero-Bolívar et al. (2023). Data were acquired at a sampling rate of 50 kHz over a 10 s interval using a National Instruments PXIe-4499.

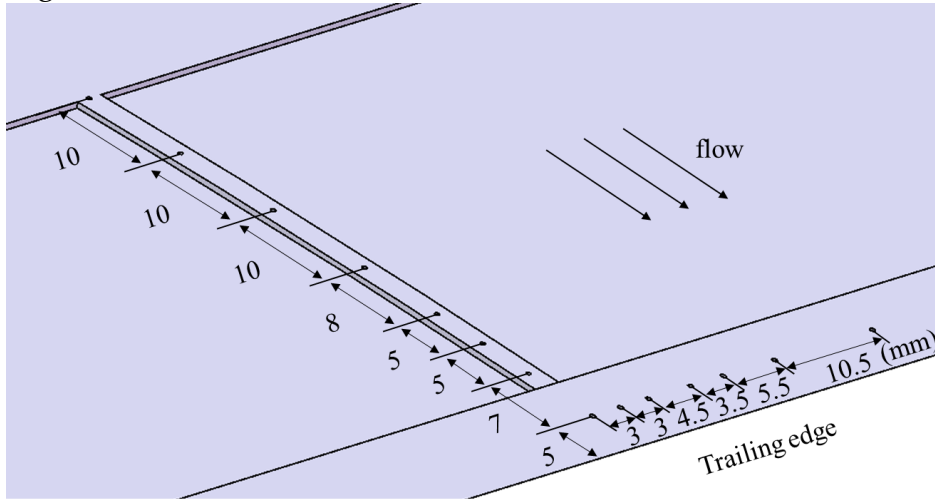


Fig.4 The distribution of the surface pressure transducers.

2.5 Particle image velocimetry

Tomographic PIV was employed to obtain the three-dimensional velocity fields in the wake of the finlets, as shown in Fig.5(a). Four high-speed CMOS cameras, including two Photron FASTCAM Mini AX100 cameras (1024×1024 pixels, $20 \mu\text{m pixel}^{-1}$) and two Phantom v2640 cameras (2048×1952 pixels, $13.5 \mu\text{m pixel}^{-1}$), were used to capture the particle images. The cameras were arranged in a cross-shaped pattern, with a maximum angle of approximately 40° between the top and bottom cameras to ensure good volume reconstruction accuracy. Objectives of 200 mm focal length were mounted for the Mini AX100 and v2640, at an angle to comply with the Scheimpflug condition. The flow was seeded with water-oil droplets approximately $1 \mu\text{m}$ in diameter and illuminated by a high-speed laser (Nd:YLF, 532 nm, Photonics Industries DM2-532-60, 12 mJ/pulse at 10 kHz) using a multi-pass light amplification system.

A Cartesian coordinate system was defined with the origin anchored at the rear of the finlets, located 7.5 mm from the spanwise symmetry plane, as shown in Fig.5(a). The y - and z -axes represent the wall-normal and spanwise directions, respectively. The x -axis is normal to the former axes to form a right-handed reference system, being parallel to the airfoil surface. The tomographic measurement domain was $30 \times 10 \times 20 \text{ mm}^3$ ($x \times y \times z$), covering a streamwise extent of $x = [-12, 18]$ mm and a spanwise extent of $z = [-10, 10]$ mm. The digital image resolution was 24.4 pixels/mm, and the pulse separation time was $26 \mu\text{s}$. The snapshots were acquired at 5000 Hz with an ensemble of 12000.

Planar time-resolved PIV measurements were then conducted to acquire the instantaneous velocity fields in the plane coinciding with the finlets, as shown in Fig.5(b). A high-speed CMOS camera (Phantom v2640, 2048×1952 pixels, $13.5 \mu\text{m}$ pixel⁻¹) was used to record particle images, fitted with a 105 mm focal length lens. The field of view spanned $74 \text{ mm} \times 18 \text{ mm}$ in the streamwise (x) and wall-normal (y) directions. Image sequences were captured at 10 kHz, yielding an ensemble of 25000 snapshots. The same seeding particles and illumination system were used as in the tomographic PIV measurements.

Raw particle images for both tomographic and planar PIV measurements were pre-processed in LaVision DaVis 10 with background subtraction, intensity normalization and Gaussian smoothing. For tomographic PIV, volume self-calibration was employed to reduce mapping errors, and the measurement volume was reconstructed using the camera simultaneous multiplicative reconstruction technique (CSMART) algorithm. The three-dimensional velocity fields were computed using a multigrid volume deformation method, with a final interrogation volume of $32 \times 32 \times 32$ voxels and 75% overlap, resulting in a vector pitch of 0.33 mm. For planar PIV, velocity fields were computed using a multi-pass cross-correlation algorithm with window deformation. A final interrogation window size of 16×16 pixels and a 75% overlap resulted in a vector pitch of 0.158 mm.

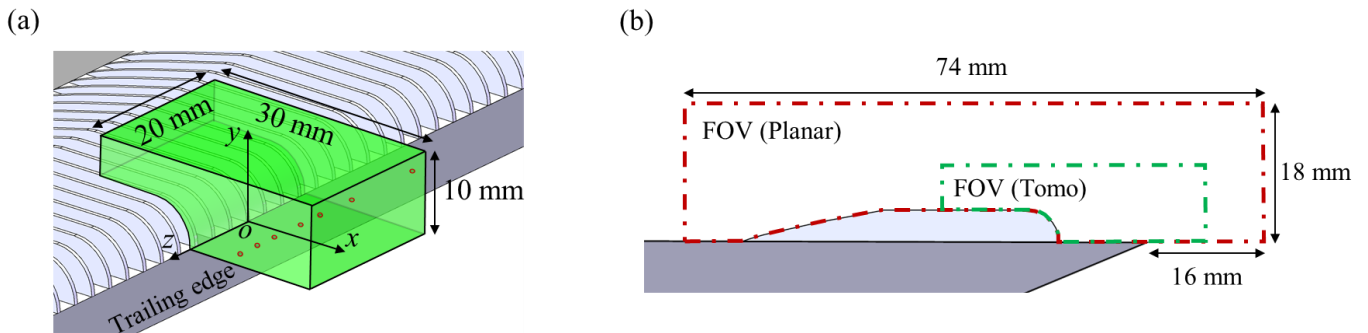


Fig.5 Schematic of the tomographic and planar PIV measurements: (a) tomographic PIV; (b) planar PIV.

3. Results

3.1 Acoustic performance

The acoustic performance of the finlet treatment is first examined using beamforming results, as shown in Fig.6. For the untreated airfoil, the dominant noise source is concentrated around the trailing-edge region at $f_c = 1250 \text{ Hz}$. After the type A finlets are applied, the source intensity in the same region is clearly reduced, indicating that the streamwise finlets suppress the main trailing-edge noise source. The other two finlet geometries give similar source distributions, and therefore only the untreated and type A cases are shown here for clarity.

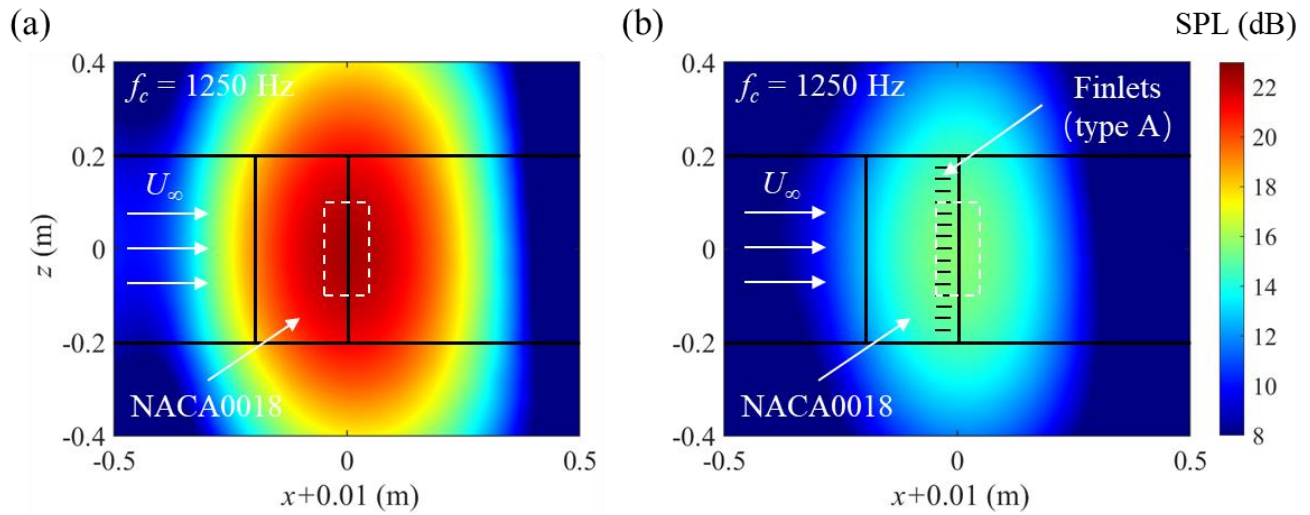


Fig.6 Beamforming results around the airfoil trailing edge at $f_c = 1250$ Hz: (a) untreated case; (b) type A finlet treatment.

To compare the acoustic performance quantitatively, Fig.7 presents the reduction of far-field sound pressure level relative to the untreated case. All finlet configurations achieve broadband noise reduction. Type A and type C show very similar attenuation levels, with the maximum reduction reaching about 6.4 dB around 1000 Hz. The reduction of type B is slightly weaker in the range of approximately 600-1600 Hz, but the difference among the three geometries is not large. This suggests that, when the spacing and height are fixed, changing the finlet profile only weakly affects the overall noise-reduction capability.

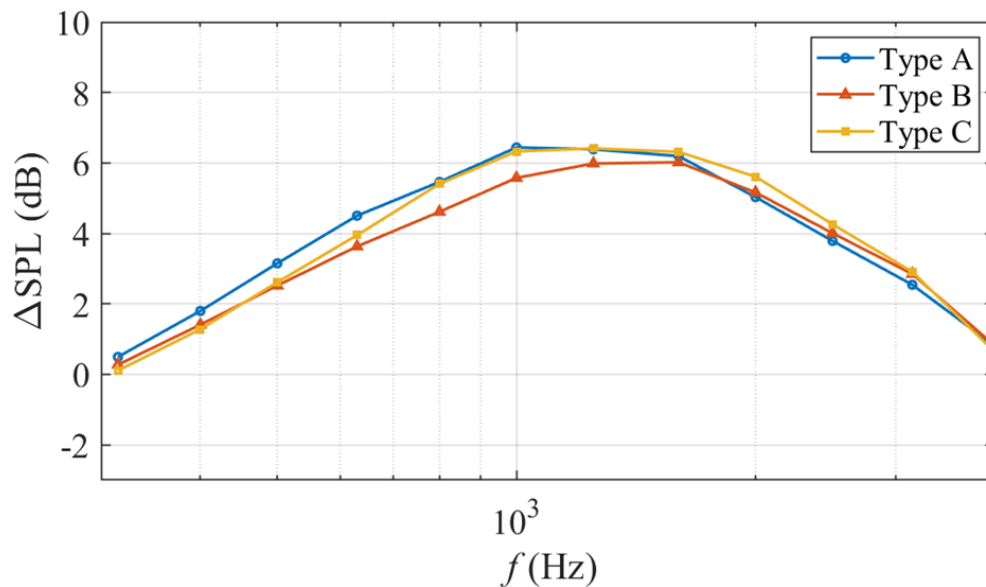


Fig.7 Far-field noise reduction and drag variation for different finlet geometries.

3.2 Aerodynamic drag characteristics

The aerodynamic drag shows a different dependence on the finlet geometry from the far-field noise. Under the present flow condition, the drag coefficient of the untreated airfoil is $C_D = 0.0253$. After applying the finlets, C_D increases to 0.0285 for type A, 0.0273 for type B, and 0.0279 for type C, corresponding to increases of 12.6%, 7.9%, and 10.3%, respectively. Although the three finlet configurations provide similar noise-reduction levels, their drag penalties are noticeably different. Type B, with a more gradual leading-edge profile, gives the smallest drag increase, whereas type A produces the largest penalty. This indicates that the aerodynamic drag is more sensitive to the detailed finlet geometry than the acoustic performance, and motivates the following analysis of the wall-pressure fluctuation pattern and flow-field response.

3.3 Unsteady wall-pressure fluctuations

The streamwise evolutions of the wall-pressure fluctuation PSD difference ($\Delta\Phi_{pp}$) between different types of finlets and the untreated case are presented in Fig.8 with an effective frequency of 100 Hz to 4000 Hz. For type A (see Fig.8(a)), the influence on pressure fluctuations upstream of the finlets is minimal. Upon entering the leading-edge section ($x/L = -1$), stronger low- and mid-frequency fluctuations are induced compared to the untreated case. As the flow develops along the plateau and trailing-edge sections, the attenuation of mid- and high-frequency fluctuations becomes increasingly pronounced. Finally, in the finlet wake ($x/L = -0.13$), a significant reduction in mid- and high-frequency energy is achieved, with negligible impact on the low-frequency pressure fluctuations. Due to the gentler slope of the leading-edge section in type B (see Fig.8(b)), the interaction between the finlets and the flow field is mitigated. Consequently, the side effect on low- and mid-frequency pressure fluctuations observed in the leading-edge region of type A is significantly suppressed. However, this modification also results in a slightly compromised attenuation of pressure fluctuations near the finlet rear and wake region, rendering it less effective than type A. The pressure fluctuations in the leading-edge region of type C (see Fig.8(c)) exhibit a pattern similar to that of type A, characterized by a distinct rise in low- and mid-frequency fluctuations at $x/L = -1$, but with a slightly reduced magnitude. The advantage of type C lies in the more effective attenuation of mid- and high-frequency fluctuations near the rear of the finlets and in the wake, particularly at $x/L = -0.3$.

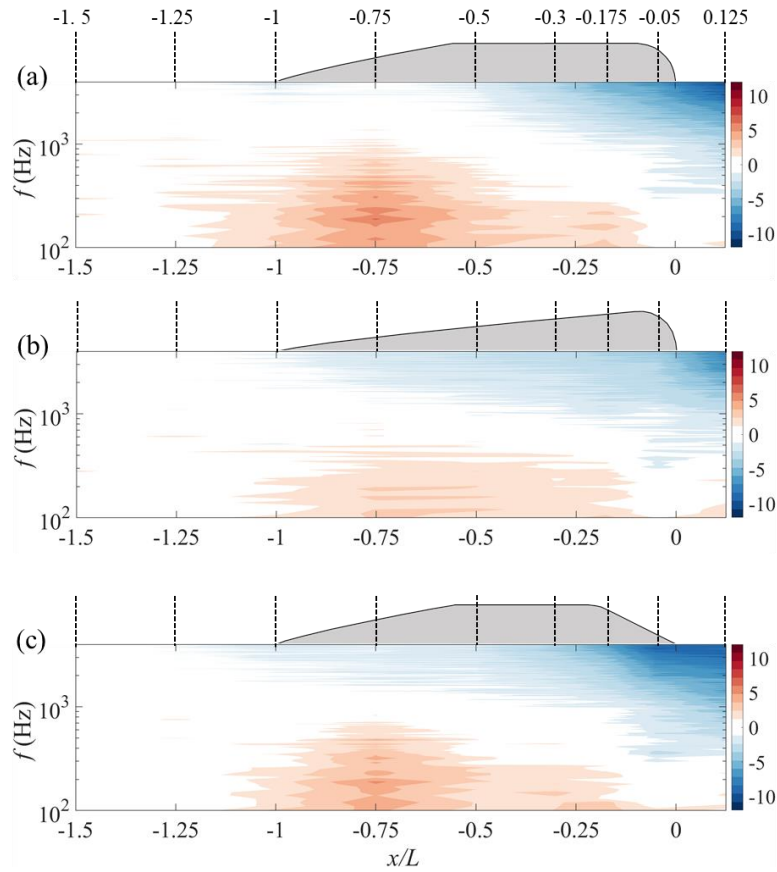


Fig.8 Contours of wall-pressure fluctuation PSD difference ($\Delta\Phi_{pp}$) between different types of finlets and the untreated case at different streamwise locations: (a) type A; (b) type B; (c) type C. The black dashed lines represent the positions of the pressure transducers.

3.4 Time-averaged flow field and turbulent statistics

The planar PIV measurements are first used to examine the mean-flow modification over a relatively large field of view. Fig.9 presents the time-averaged streamwise velocity difference relative to the untreated case and the Reynolds shear stress distributions for the three finlet geometries. A velocity deficit appears downstream of the finlet rear and above the treated region for all cases, indicating that the finlets modify the momentum distribution in the boundary layer. Compared with type A (see Fig.9(a)), type B (see Fig.9(c)) shows a weaker velocity deficit around the leading-edge section, which is consistent with the reduced disturbance introduced by the more gradual front profile. However, the deficit near the finlet rear remains close to that of type A because these two configurations share a similar rounded rear shape. For type C (see Fig.9(c)), the smoother rear profile reduces the local velocity deficit near the finlet rear.

The Reynolds shear stress contours in Fig.9(b,d,f) show that a detached shear layer is formed above the finlets for all cases. The leading-edge geometry mainly changes the onset and wall-normal position of this shear layer. For type B (see Fig.9(d)), the high-shear region appears farther

downstream, while the peak is located closer to the wall and becomes locally stronger. This indicates that the more gradual leading edge weakens the initial interaction with the incoming flow, but the shear layer develops closer to the wall downstream. Type C (see Fig.9(f)) exhibits a shear-layer pattern close to type A in the upstream part of the finlet, whereas the velocity deficit near the rear part is reduced by the modified rear shape.

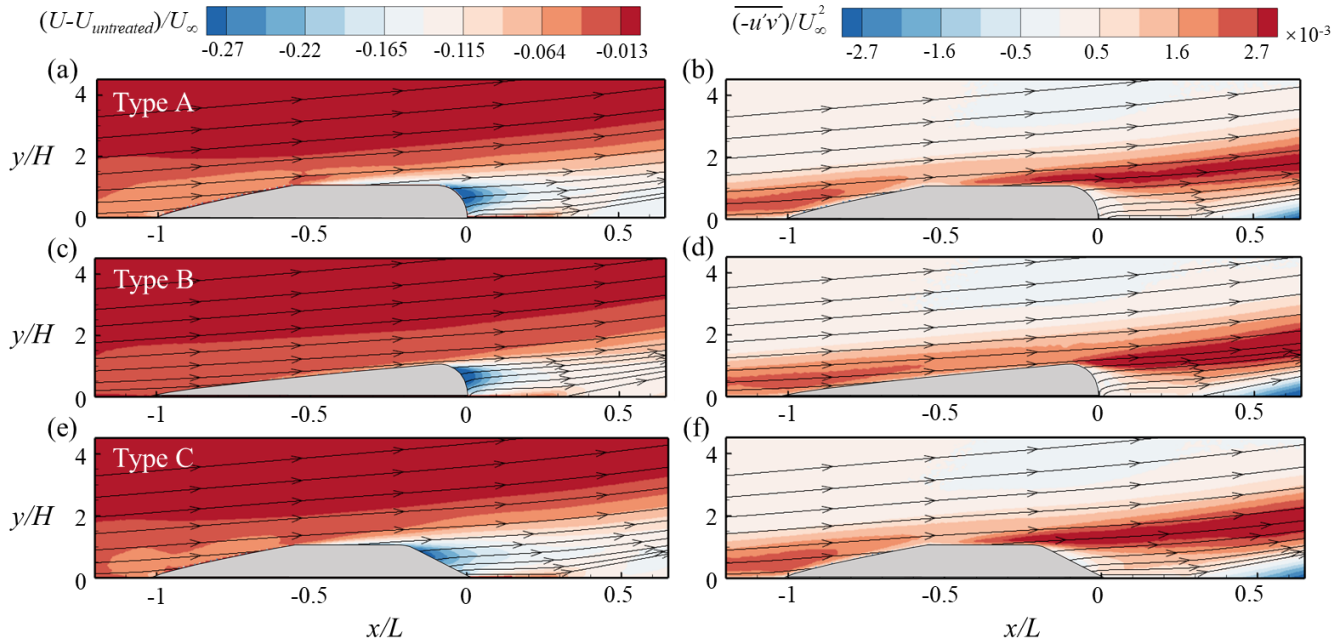


Fig.9 Contours of time-averaged streamwise velocity difference and Reynolds shear stress for different finlet geometries: (a,b) type A; (c,d) type B; (e,f) type C.

The profiles extracted at $x/L = 0.13$ provide a more direct comparison of the wake characteristics, as shown in Fig.10. For the velocity-deficit profiles in Fig.10(a), all three finlet configurations produce a pronounced velocity reduction around $y/H = 0.75$, corresponding to the wake region behind the finlets. Type A shows the largest velocity deficit, with the minimum value reaching approximately $-0.22U_\infty$. For type B, the affected region is narrower than that of type A, and the velocity deficit above the finlet height is reduced, especially for $y/H > 1.2$. This weaker momentum loss is consistent with its smallest drag increase. Type C exhibits a profile close to type A above the finlet height, but the deficit within and below the finlet-height region is smaller than that of type A, which also contributes to the lower drag penalty compared with type A. Fig.10(b) compares the Reynolds shear stress profiles at the same streamwise location. Compared with the untreated case, the finlet treatments suppress the near-wall Reynolds shear stress and generate a new peak around the detached shear layer. Type A and type C show similar peak locations around $y/H = 1.4$, while type C has a slightly stronger value in this region. Type B exhibits the strongest Reynolds shear stress peak, reaching approximately 4.2×10^{-3} , and this peak is located closer to

the wall at around $y/H = 1.1$. The closer and stronger shear-layer activity in type B is consistent with the contour results in Fig.9, and may explain why its wall-pressure fluctuation and far-field noise reduction are slightly weaker than those of type A and type C.

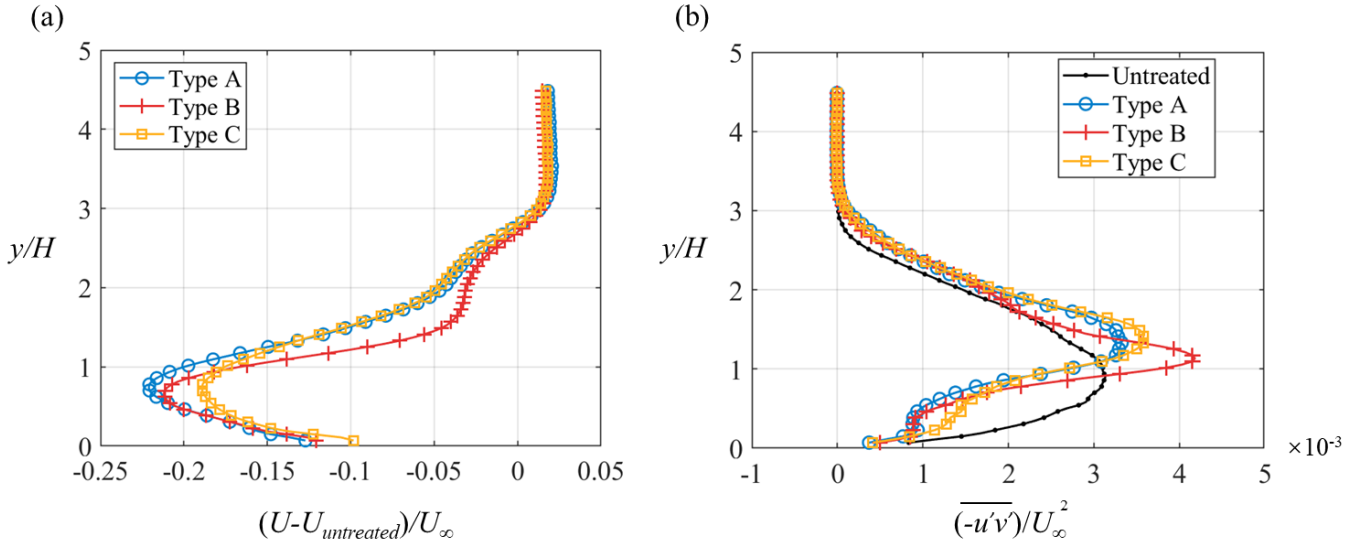


Fig.10 Profiles of (a) time-averaged streamwise velocity difference and (b) Reynolds shear stress extracted at $x/L = 0.13$.

The reverse-flow probability is calculated as $\gamma_{rev}(x, y) = \Pr[u(x, y, t) < 0]$, where u is the instantaneous streamwise velocity. The black dashed line in Fig.11 represents the contour of $\gamma_{rev} = 0.1$. For type A (see Fig.11(a)), a distinct reverse-flow region appears near the rounded finlet rear. The $\gamma_{rev} = 0.1$ contour extends downstream to approximately $x/L = 0.15$ and reaches a wall-normal height of about $y/H = 0.4$, indicating that reverse-flow events occur repeatedly in a relatively broad near-wall region. Type B (see Fig.11(b)) shows a similar distribution because it has the same rounded rear profile as type A, but the $\gamma_{rev} = 0.1$ envelope is slightly thinner and remains closer to the wall. For type C (see Fig.11(c)), the reverse-flow probability is clearly reduced, and the $\gamma_{rev} = 0.1$ contour is much shorter and confined to a thinner region near the wall. The enlarged reverse-flow region for the rounded rear profile suggests stronger local recirculating motions near the finlet rear. These events may form a local low-pressure region behind the finlet and increase the pressure difference across the finlet, thereby contributing to the larger drag penalty. The other influence of these near-wall unsteady events will be further discussed in the spectral analysis.

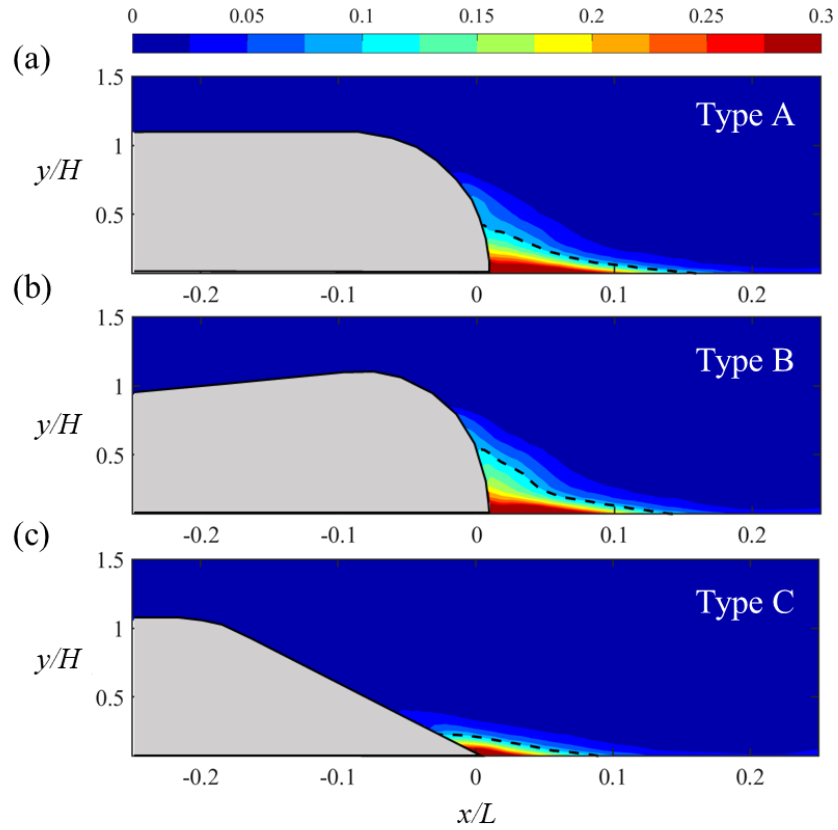


Fig.11 Reverse-flow probability (γ_{rev}) distributions: (a) type A; (b) type B; (c) type C. The black dashed line represents $\gamma_{rev} = 0.1$

3.5 Instantaneous three-dimensional flow structures

The modification of turbulent structures by finlets is critical, as these vortical motions are closely related to the generation of wall-pressure fluctuations (Ghaemi & Scarano, 2013; Thomas & Bull, 1983). The instantaneous three-dimensional flow structures are identified using the λ_2 criterion (Jeong & Hussain, 1995), as shown in Fig.12. For the untreated case (Fig.12(a,b)), large-scale streaky structures are observed within the boundary layer. These structures are elongated in the streamwise direction and remain close to the wall, representing the typical wall-attached motions in turbulent boundary layers (Adrian, 2007; Chen & Ye, 2026; Feng & Ye, 2023). Such near-wall structures can contribute to wall-pressure fluctuations because of the direct interaction between them and the airfoil wall.

For type A (Fig.12(c,d)), the original near-wall streaky structures are strongly disrupted after the finlets are applied. The visible vortical structures are mainly redistributed into the detached shear-layer region above the finlet, where newly generated hairpin-like vortices can be observed. Meanwhile, the near-wall region behind the finlet contains fewer large-scale streaky structures than the untreated case. This indicates that type A weakens the direct interaction between the

original near-wall turbulent structures and the wall, which is consistent with the reduction of wall-pressure fluctuations shown in Fig.8. For type B (Fig.12(e,f)), the more gradual leading edge reduces the direct interaction between the incoming flow and the front part of the finlet. As a result, some convected streaky structures can still be identified and are lifted along the leading-edge slope before being reorganized downstream. For type C (Fig.12(g,h)), the overall instantaneous flow pattern is similar to that of type A, suggesting that the modification of the rear profile does not significantly change the main redistribution process of the turbulent structures. A local increase in vortical structures can be observed near the finlet rear, which is likely associated with the smoother rear profile of type C.

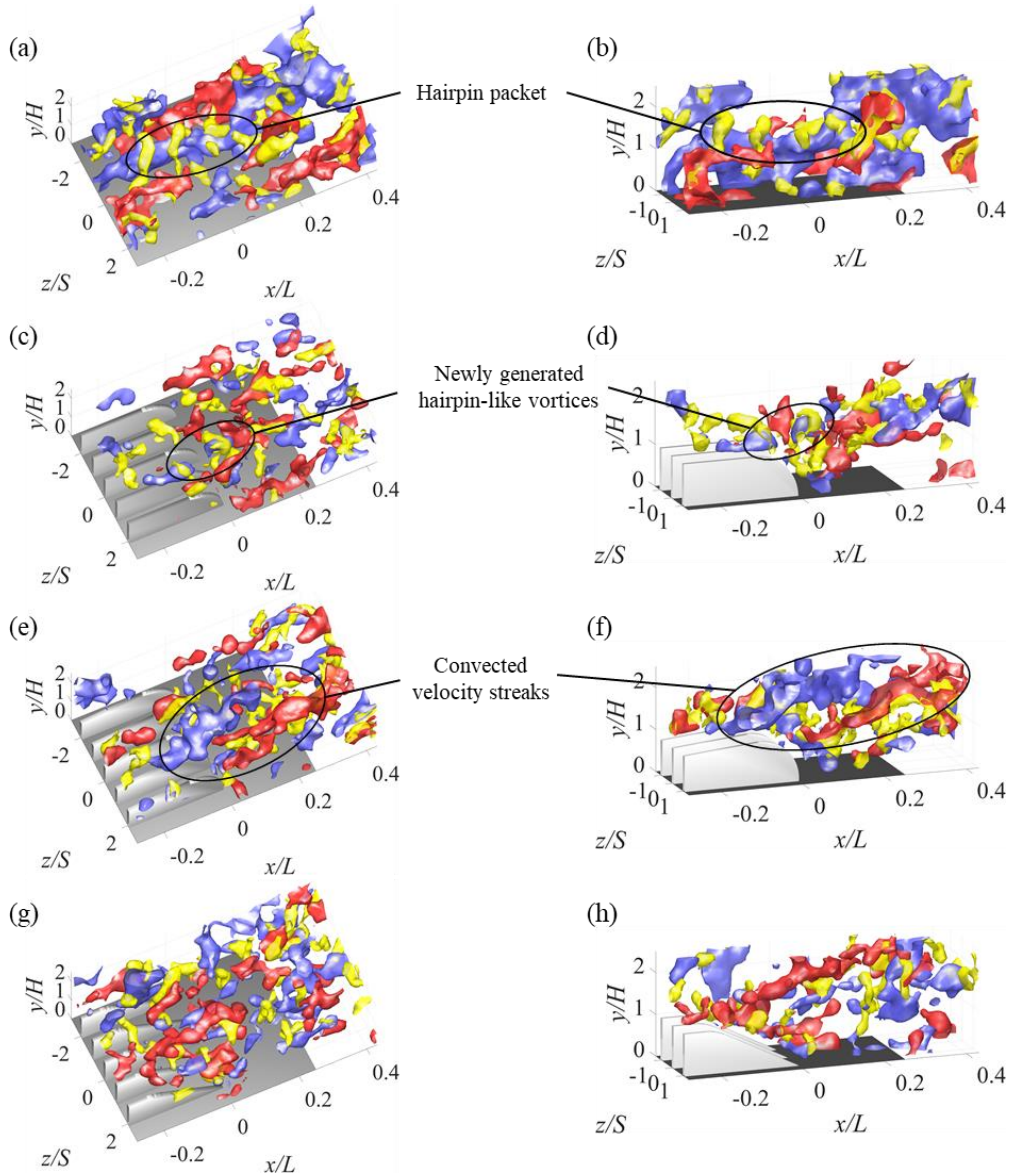


Fig.12 Instantaneous flow patterns for different configurations from two perspectives: (a,b) untreated case; (c,d) type A; (e,f) type B; (g,h) type C. The yellow iso-surface represents the λ_2 criterion of -2.2×10^{-6} . The red and blue iso-surfaces indicate the high- and low-speed patches of $u'/U_\infty = \pm 0.11$.

To quantify the wall-normal organization of vortical structures, a structure-count statistic based on the λ_2 criterion is calculated from the tomographic PIV fields, as shown in Fig.13. For each instantaneous field, vortical regions are identified using $\lambda_2 \leq -2.2 \times 10^6$. Connected components are then detected in three dimensions, and only structures containing at least 70 voxels are retained. This minimum-volume criterion is used to remove isolated noisy fragments and poorly resolved objects. The centroid height of each retained structure is assigned to a wall-normal bin for the height-distribution statistics.

At $x/L = 0.03$, the untreated case exhibits a distinct near-wall peak of the vortical structures, corresponding to the original wall-attached turbulent motions. After applying finlets of type A, the near-wall structure count is reduced, while a new peak appears at a higher wall-normal position around the detached shear-layer region. This indicates that the finlets disrupt part of the original near-wall vortical motions and redistribute the structures above the finlet. Compared with type A, type B shows a stronger peak located closer to the wall, which is consistent with the lower shear-layer position observed in the Reynolds shear stress results. Type C exhibits a distribution generally similar to that of type A, but more structures are observed near the wall close to the finlet rear. This local increase agrees with the result in Fig.12(g,h), where more vortical structures appear around the smoother rear profile of type C. At $x/L = 0.13$ and 0.23 , the wall-normal location of the structure-count peak moves upward downstream, following the development of the shear layer. Among the three finlet geometries, the profiles of type A and type C remain close to each other, whereas type B still shows a peak located closer to the wall and a relatively larger number of structures around the shear-layer height. This distribution is consistent with its slightly weaker wall-pressure fluctuation and far-field noise reduction.

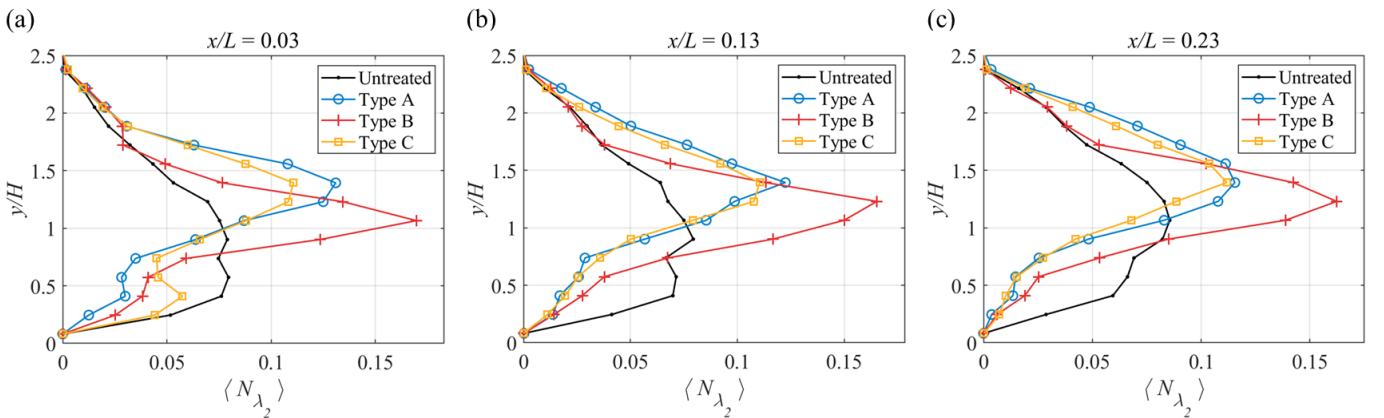


Fig.13 Wall-normal distributions of the mean number of resolved λ_2 structures at different streamwise locations: (a) $x/L = 0.03$; (b) $x/L = 0.13$; (c) $x/L = 0.23$.

3.6 Spectral characteristics of streamwise velocity fluctuations

To further examine the turbulent energy associated with streamwise velocity fluctuations, Fig.14 presents the premultiplied power spectral density ($f\Phi_{uu}/U_\infty^2$) obtained from planar PIV for higher sampling frequency. In Fig.14, the black dashed contours denote $f\Phi_{uu}/U_\infty^2 = 0.0025$, and the white dashed line indicates the finlet height ($y/H = 1$). Near the finlet rear ($x/L = 0.03$), the untreated case shows a high-energy region mainly close to the wall. After applying the finlets, the dominant energy region is shifted upward and is mainly concentrated around the detached shear layer. However, for type A (see Fig.14(c)), an additional high-frequency energy region appears near the wall below the finlet height, which is consistent with the stronger reverse-flow events observed near the rounded rear profile in Fig.11. Type B (see Fig.14(e)) shows a similar but weaker high-frequency near-wall region because it has the same rounded rear profile as type A. Meanwhile, the main energy region associated with the shear layer is located closer to the wall and has a lower energy level than that of type A, consistent with the lower shear-layer position observed in the Reynolds shear stress and λ_2 statistics. For type C (see Fig.14(g)), the dominant energy region is comparable to that of type A in the shear-layer region, but the near-wall high-frequency energy below the finlet height is weakened. This indicates that the smoother rear profile reduces the local high-frequency unsteadiness near the finlet rear.

Farther downstream at $x/L = 0.13$, the spectra of the three finlet configurations become more similar. The near-wall high-frequency energy observed near the finlet rear is largely reduced, and the dominant energy region remains around or above the finlet-height position. This suggests that the local high-frequency unsteadiness induced near the rounded rear profile decays rapidly in the streamwise direction. Therefore, although the rear-profile shape affects the local reverse-flow events and high-frequency velocity fluctuations near the finlet rear, its influence on the downstream spectral distribution is limited. This explains why the three finlet geometries show similar far-field noise reduction. It also indicates that the finlet rear should not be placed too close to the airfoil trailing edge, because the additional high-frequency unsteadiness generated near the finlet rear may reach the trailing edge and introduce extra disturbances.

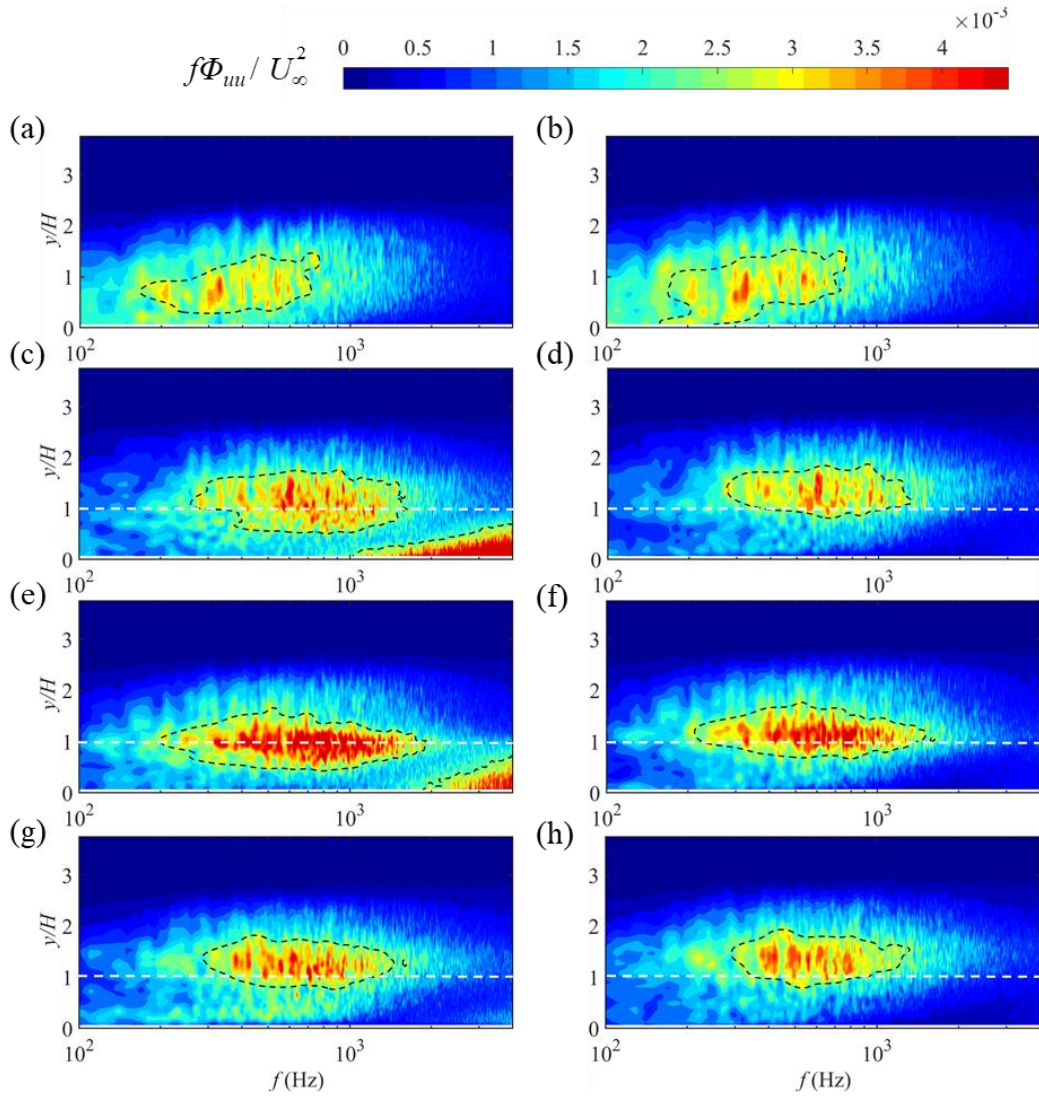


Fig.14 The premultiplied power spectral density ($f\Phi_{uu}/U_{\infty}^2$) of streamwise velocity fluctuations for the different finlet types near the finlet rear ($x/L = 0.03$) and downstream ($x/L = 0.13$), respectively: (a,b) untreated case; (c,d) type A; (e,f) type B; (g,h) type C. The black dashed contours denote $f\Phi_{uu}/U_{\infty}^2 = 0.0025$, and the white dashed lines indicate $y/H = 1$.

4. Conclusion

In the present study, streamwise finlets with different leading-edge and rear profiles are applied near the trailing edge of a NACA0018 airfoil to investigate how finlet geometry attenuates wall-pressure fluctuations and trailing-edge noise through the modification of boundary-layer turbulent structures, while affecting the associated drag penalty. All finlet configurations disrupt the original near-wall streaky structures and redistribute vortical motions within the boundary layer. This reduces the direct influence of near-wall turbulent structures on the wall, leading to attenuation of wall-pressure fluctuations and broadband trailing-edge noise reduction. Although the three configurations provide similar noise reduction, their drag penalties differ noticeably, indicating that the detailed finlet geometry remains important for aerodynamic performance.

The leading-edge profile mainly affects the interaction between the incoming boundary layer and the front part of the finlet. A more gradual leading edge weakens the initial disturbance to the incoming flow and reduces the velocity deficit, which contributes to a lower drag penalty. However, the detached shear layer formed downstream is located closer to the wall, and the corresponding Reynolds shear stress and vortical structure distributions indicate stronger near-wall turbulent activity. This is consistent with the slightly weaker wall-pressure fluctuation and far-field noise reduction.

The rear profile mainly influences the local flow events near the finlet rear. A rounded rear profile produces stronger low-speed and reverse-flow events, which are accompanied by additional high-frequency streamwise velocity fluctuations near the wall. These local unsteady motions may increase the pressure difference around the finlet and contribute to a larger drag penalty. In contrast, a smoother rear profile weakens the local reverse-flow region and reduces the near-wall high-frequency fluctuation energy, leading to a lower drag increase. Overall, the results suggest that finlet geometry should be designed to preserve the redistribution of boundary-layer turbulent structures while suppressing local unsteady events that increase drag.

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