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Airfoil Trailing Edge Noise Reduction by Application of Finlets

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This experimental study investigates the effect of bio-inspired finlets on the reduction of trailing edge noise of a NACA 0012 airfoil. At a chord-based Reynolds number of 400,000, the far-field noise measurements show that the finlets are capable of reducing the trailing edge noise effectively from 1,000 Hz to 4,000 Hz with up to 6 dB reduction, for effective angles of attack from zero to eight degree. By correlating the far-field noise to the boundary layer measurements, an optimal finlet height to boundary layer thickness ratio to achieve the highest noise reduction is discussed. Static pressure and dynamic pressure fluctuations are examined, particularly within the finlet-treated area, to capture the flow dynamics through the treatments. The unsteady surface pressure fluctuation spectra show strong reduction at frequencies higher than 1,000 Hz in the finlet wake, complying with the far-field measurements. Both the auto- and cross-correlation results of the unsteady surface pressure reveal the formation of large-scale turbulence at the entrance and toward the exit of the finlets. Moreover, they suggest that the formation and subsequent mixing of these large-scale structures with the boundary layer can be beneficial to reducing the unsteady surface pressure fluctuations. The findings will be useful to potential optimization of the finlets.

Nomenclature

C	=	airfoil chord length (mm)	C_p	=	pressure coefficient
$C_{p, \text{rms}}$	=	pressure coefficient root-mean-square	d_F	=	finlet distance to airfoil leading edge (mm)
f, f_c	=	frequency, center frequency (Hz)	h_F, h_N	=	finlet height, nozzle height (mm)
l_F, l_N	=	finlet length, nozzle length (mm)	p_0	=	reference pressure (Pa)
p'_{rms}	=	pressure fluctuation root-mean-square (Pa)	Re	=	chord-based Reynolds number
R_{pp}	=	pressure auto-correlation coefficient	s_F	=	finlet spacing (mm)
St	=	Strouhal number fh/U_∞	t	=	time (s)
U_∞	=	free-stream velocity (m s^{-1})	U_c	=	convection velocity (m s^{-1})

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U_e	=	velocity outside the boundary layer edge (m s^{-1})	u	=	streamwise velocity (m s^{-1})
u'_{rms}	=	velocity fluctuation root-mean-square (m s^{-1})	x, y, z	=	Cartesian coordinate system (mm)
x_F, y_F	=	local finlet coordinate system (mm)	α, α_e	=	geometric, effective angle of attack ($^\circ$)
Δx	=	transducers separation distance (mm)	δ	=	boundary layer thickness (mm)
Λ	=	length scale (mm)	$\mathcal{T}$	=	integral time scale (s)
τ	=	time lag (s)	ϕ_{pp}	=	pressure power spectral density (dB Hz^{-1})

I. Introduction

THE successful reduction of engine noise in recent decades has rendered the reduction of airframe, and thus trailing edge noise, necessary when aiming for an overall noise reduction of aircraft [1]. Airfoil trailing edge noise can be attributed mainly to the interaction of the turbulent boundary layer with the sharp trailing edge if the Reynolds number is large enough [2, 3]. Under such circumstances, the far-field noise level can be related to the surface pressure fluctuations and the spanwise correlation length of turbulence structures at the trailing edge of the airfoil, using the mathematical description based on Amiet's theory [4]. Thus, in order to mitigate the trailing edge noise, it is necessary to decrease either the spanwise correlation length or the unsteady surface pressure fluctuations through modifying the turbulence structures interacting with the sharp trailing edge. Since an accurate prediction of the unsteady surface pressure fluctuations in the turbulent boundary layer is complex and depends on the history of the turbulent boundary layer [3], detailed experimental results are essential to understand the effects of altered flow conditions on trailing edge noise.

Specific modifications of a turbulent boundary layer to reduce trailing edge noise can be achieved by active and passive flow control strategies. Active flow control requires additional energy input to alter the turbulent boundary layer. This is generally realized with boundary layer injection [5, 6] or boundary layer suction [7, 8]. While noise reduction over broadband frequency ranges has been achieved using active flow reduction techniques [5], various passive flow control techniques have also been observed to efficiently reduce the trailing edge noise, without additional energy requirements. The majority of the passive noise reduction approaches can be related to features of silent-flight owl species. The detailed features from which different passive noise reduction strategies were derived have been summarized by Lilley [9]. Those relevant to trailing edge noise are trailing edge serrations [10–14], trailing edge brushes [15], porous trailing edges [16–18] and finlet treatments [19–24]. These passive techniques lead to a decrease of trailing edge noise emission of airfoils and flat plates, yet according to Lilley [9], the most efficient techniques in reducing noise above 2,000 Hz for a Reynolds number of $Re \approx 150,000$ should be, in theory, those reproducing the features of the downy fiber structure on the surface of owl feathers, which include porous structures and finlets.

Clark *et al.* [19, 20] introduced finlets as the most promising surface treatments out of the investigated rail- and

fence-type constructs in order to model the canopy structures formed by the hairs of the owl feathers. Applying these finlets either flush with or extended beyond the trailing edge of a DU96-W180 airfoil, Clark *et al.* [20] observed up to 10 dB broadband trailing edge noise reduction. Moreover, it was predicted that the noise reduction efficiency of finlets would not be affected by shifting the treated area further upstream. The underlying physical principles of finlets applied upstream of the trailing edge were experimentally investigated by Afshari *et al.* [21] using a flat plate. Afshari *et al.* [21] reported that the physical trends from their measurements were independent of the Reynolds number considered in the range between $Re = 387,000$ and $Re = 773,000$. They also found that "channeling" contributes to the trailing edge noise reduction, if the spacing between the wall-structures of the finlet treatments is large enough. Given the sufficiently large spacing, the turbulence is convected through the space (channels) between the finlet walls, and thereby its turbulent energy is dissipated through friction on the surface of the finlets. Moreover, they observed that if the spacing falls below a certain threshold, the surface pressure fluctuations near the trailing edge, and thus the emitted noise, increases compared to the untreated configuration at frequencies lower than 1,000 Hz or a Strouhal number of $St = 0.6$. This phenomenon was explained with the shear layers originating along the top of the finlet treatments, which eventually separate from the finlets near their trailing edges. The turbulence structures, forming in the wake of the finlets as a result of these free shear layers, cause an increase in the unsteady surface pressure fluctuations and hence the noise emission at relatively low frequencies. It was reported further by Afshari *et al.* [22] that the formation of the shear layers may be reduced by adding a third dimension to the finlet design, i.e. by adding staggered finlet rows to a given treatment. Applying Amiet's model [4] for trailing edge noise using the measured surface pressure fluctuation power spectral density (PSD) and the spanwise length scale as input, the performance of these "3d finlets" was found to improve compared to the conventional finlets.

A numerical investigation of the finlets applied on a NACA 0012 airfoil, applied flush with its trailing edge, was carried out by Bodling and Sharma [23]. The reduction of the surface pressure fluctuations at frequencies above 2,000 Hz for a chord-based Reynolds number of $Re = 500,000$ combined with an increase at lower frequencies was attributed to the lifting of turbulent eddies away from the airfoil surface. Evaluating surface pressure data within the finlet-treated area, Gstrein *et al.* [24] also identified a similar effect on the turbulence structures, when the surface treatments were applied upstream of the trailing edge. Comparing these observations with those obtained from a flat plate suggests that the noise reduction mechanisms may differ between an airfoil and a flat plate set-up.

The majority of previous studies on finlet treatments have focused on the boundary layer characteristics in the finlet wake and at the trailing edge. The results suggested that the understanding of the flow as it enters the finlets is equally important in fully capturing the evolution of the flow structures and hence understanding the physical noise reduction mechanisms of the finlet treatments. Based on the findings of the previous work, the present investigation aims to provide a detailed account of the pressure and velocity fields on a NACA 0012 airfoil treated with finlets. Emphasis is placed on the development of the surface pressure fluctuations from upstream of the treated area through the "channels"

in between of the finlet wall-structures until reaching the airfoil trailing edge. Building upon the preliminary study conducted by Gstrein *et al.* [24], which attempted to identify the effects of varying finlet parameters, such as length, spacing and position, and to establish an optimal configuration for trailing edge noise reduction, the present study examines a few selected finlets with a fixed position on the airfoil chord. Focusing on a detailed description of the flow development along the chord of the treated airfoil and the role of finlets in reducing the radiated far-field noise, the results shed light on the changes of pressure and velocity fields as well as the corresponding turbulent length scales on the finlet-treated airfoil beneficial to mitigating the trailing edge noise. The experimental set-up and used measurement techniques are presented in Section II. In Section III, the experiment results are discussed, including the far-field sound pressure level, the boundary layer velocity profiles, and the static and the dynamic pressure fields. Finally, concluding remarks are given in Section IV.

II. Experimental Set-up

The experiments were performed in the open-jet test section of the aeroacoustic facility at the University of Bristol. This test section is anechoic above 160 Hz and is connected to a temperature-controlled closed-circuit wind tunnel. With a rectangular nozzle of $l_N = 500$ mm width and $h_N = 775$ mm height at the nozzle exit (see Figs. 1a and 1b), uniform flow speeds from $U_\infty = 10 \text{ m s}^{-1}$ to $U_\infty = 40 \text{ m s}^{-1}$ can be reached. A more thorough description of the aeroacoustic facility can be found in [25].

To measure the far-field noise, a beamforming array was installed directly above the airfoil. The position and strength of the main noise source were determined using a delay-and-sum algorithm implemented within the Acoular software package [26]. In order to obtain the spectra, the far-field sound pressure level (SPL) was calculated as $\text{SPL} = 20 \log_{10} (p'_{\text{rms}}/p_0)$ for one-twelfth octave frequency bands with different center frequencies. Here, p'_{rms} designates the root-mean-square of the far-field sound pressure fluctuations, and $p_0 = 20 \text{ } \mu\text{Pa}$, the reference pressure. All sound pressure levels determined for various center frequencies, f_c , were integrated over an area representative of the origin of trailing edge noise of the NACA 0012 airfoil. This source integration area is also illustrated in Fig. 2, together with three representative beamforming contour maps at a center frequency of $f_c = 1,060$ Hz. The configuration and coordinate labels are defined in Fig. 1 and Table 1. The beamforming array used in this study consists of 64 Panasonic WM-61A microphones arranged along 9 spiral arms, as shown in Fig. 1a, which have an uncertainty of 1.5 dB for a 95 % confidence interval [27]. Figures 1a and 1b depict the beamforming array and the arrangement of the microphones, respectively. The actual beamforming response to a point source was evaluated with a VISATON FRS 8 speaker, excited at discrete frequencies between 500 Hz and 4,000 Hz. It was observed that the response matched well with the simulated point source at these frequencies and thus it is expected that the present beamforming array captures the far-field sound correctly within the frequency range between 500 Hz and 4,000 Hz. Moreover, with reference to Yardibi et al. [28], the measurement uncertainty of the beamforming array was estimated to be approximately 1.5 dB below 2,500 Hz and

Fig. 1 Experimental set-up: (a) Test rig overview, (b) Airfoil placement and acoustic beamformer alignment with the airfoil trailing edge mid-span (top view of Fig. 1(a)) and (c) Finlet schematic diagram and design parameters (see Table 1).

approximately 2 dB at even higher frequencies, taking into account the averaging and calibration errors. For a more thorough description of the presented beamforming method and the applied array the reader is referred to [29].

A NACA 0012 airfoil with a chord length of $C = 300\text{ mm}$ and an airfoil span length of $l_A = 500\text{ mm}$ was used for this study. The airfoil is equipped with Knowles FG-23629-P16 pressure transducers mounted beneath pin holes with a diameter of 0.4 mm , which are oriented normal to the airfoil surface. This installation method ensures minimal pressure attenuation effects due to averaging by reducing the sensing area of the pressure transducers [30]. Close to the trailing edge ($x \geq 0.95C$), the airfoil is thin and does not allow for a conventional in-situ pressure transducers mounting. Instead, Panasonic WM-61A microphones are installed in a remote sensing configuration, i.e. the dynamic pressure information is carried to the microphone via plastic tubing. A detailed description of the applied remote sensing method is given by Vemuri *et al.* [31] for a similar configuration. The direct and remote sensing transducers are arranged along the center line of the chord. A thorough description of the NACA 0012 airfoil, its instrumentation and the aerodynamic and aeroacoustic characteristics can be found in [32, 33]. During the experiments, dynamic pressure field data were sampled at 2^{15} Hz for 24 s. To obtain the surface pressure fluctuation power spectral density, ϕ_{pp} , the Welch method was applied using a Hamming window with a window size of 2^{12} samples and 50 % overlap yielding to the interim result $p_{rms}^2(f)$,

which was then transformed to $\phi_{pp} = 10 \log_{10} \left(p_{rms}^2(f)/p_0^2 \right)$. Details about the application of the Welch method can be found in [34]. Both the dynamic transducers embedded in the airfoil and the beamforming array were calibrated against a G.R.A.S. 40PL reference microphone in the frequency domain, which in turn was calibrated using a G.R.A.S. 42AA pistonphone. The calibration of the miniature microphones under the pinholes inside the airfoil, as well as the free-field microphones used for beamforming were performed inside the anechoic chamber prior to the tests. The same procedure has already been applied in previous studies [5, 17, 35].

In addition to the dynamic pressure transducers, the airfoil also has static pressure ports along the chord. The pressure information was registered by two Chell μ DAQ-32DTC Smart Pressure Scanner via polyurethane tubing of about 1 m length. Static pressure data were sampled at a rate of 1,000 Hz for 60 s. Using the error-propagation method according to Kline and McClintock [36], Mayer [29] determined the measurement uncertainty of the pressure coefficient to be ± 0.064 , taking into account the accuracy of the pressure scanners, the velocity fluctuations and the density variations in the facility. The boundary layer measurements at various locations along the airfoil chord were performed with a Dantec 55P15 hot-wire boundary layer probe, operated by a Dantec Streamline Pro system with a CTA91C10 module and calibrated using a Dantec 54H10 calibrator. The hot-wire measurements were carried out with a sampling frequency of 2^{15} Hz and a sampling duration of 16 s.

A Cartesian coordinate system (x, y, z) is used to describe the installation and positioning of the airfoil in the open-jet test section. The coordinate system is placed on the leading edge (LE) of the airfoil, where x represents the streamwise direction, y lies in the plane of the nozzle orifice and is orthogonal to the airfoil center line, and z represents the spanwise direction, respectively. The NACA 0012 airfoil was mounted between two side walls secured to the nozzle, with a distance $x = 255.5$ mm from the nozzle orifice. As indicated in Figs. 1a and 1b, the airfoil and the beamforming array were installed in the facility such that the center of the airfoil trailing edge (TE) was aligned with the beamforming array center at an angle of attack of zero degree, with a vertical distance of $y = 1$ m. The airfoil was tripped at $x/C = 0.1$ to form a turbulent boundary layer on both the pressure and the suction side using a 60° zig-zag turbulator tape of 6 mm overall width and 0.5 mm thickness. For the present investigation, the airfoil was exposed to a uniform flow speed of $U_\infty = 20 \text{ m s}^{-1}$, which is equivalent to a chord-based Reynolds number of $Re = 400,000$. In order to investigate the noise reduction capability of finlet surface treatments at different angles of attack, the NACA 0012 airfoil was rotated about its quarter chord using a turntable system, as shown in Fig. 1a. Due to the flow deflection in an open jet, the angle of attack, α , has to be corrected. The correction method used in the present study follows that of Brooks *et al.* [37], which has also been employed in a number of relevant studies for similar configurations [16, 38, 39]. The effective angle of attack α_e was obtained by

$$\alpha_e = \frac{\alpha}{\eta}, \quad (1)$$

where

$$\eta = (1 + 2\sigma)^2 + \sqrt{12\sigma}, \quad (2)$$

$$\sigma = \frac{\pi^2}{48} \left(\frac{C}{h_N} \right)^2, \quad (3)$$

and h_N is the nozzle height and equivalent to the vertical stream width. The chordwise location along the airfoil will be presented using the non-dimensional quantity x/C in the following, where both the coordinate x and the chord C are shown separately in Fig. 1a.

The design of the finlet surface treatments was inspired by Clark *et al.* [20] and Afshari *et al.* [21] and is depicted in Fig. 1c. The treatments consist of wall-structures, the finlets, arranged in parallel and with a specified distance to each other. When applied, these finlets are oriented in the streamwise direction and their main characteristics are the maximum finlet height, h_F , the spacing between the finlet wall-structures, s_F and the total length, l_F , as shown in Fig. 1c. To allow for a smooth flow transition of the boundary layer at the leading edge of the finlet, its front part is shaped according to the formula

$$y_F = ax_F^{4/5}, \quad (4)$$

which is proportional to the development of the turbulent boundary layer thickness on a flat plate [40]. In Eq. (4), x_F and y_F are the coordinates in streamwise and wall-normal direction at the leading edge of the finlets with values in mm and a denotes a constant. The value of a results from the constraint that the length of the finlet section shaped according to Eq. (4) is equal to $x_F = 33$ mm (i.e. approximately half of the finlet length). The individual finlet wall structures are 0.5 mm thick and 3d printed on a 0.3 mm thick substrate layer. The substrate layer was able to conform to the slight curvature of the airfoil profile at a certain distance d_F from the airfoil leading edge when being installed. For each treated configuration of the NACA 0012 airfoil, the airfoil span length was fully covered by finlets, and subsequently the substrate layer was locally removed to uncover the pressure sensors of the airfoil, as indicated in Fig. 1b.

III. Results and Discussion

In this section, the experimental results ranging from far-field noise to boundary layer velocity profiles, static and dynamic surface pressure for various finlet treatments are presented to shed light on the modifications of the pressure and flow fields. To understand the roles of the individual finlet parameters introduced in Fig. 1 on trailing edge noise, five different finlet treatments are considered. The results for the untreated NACA 0012 airfoil, referred to as the baseline configuration, are also provided for comparison. Table 1 lists the different finlet configurations investigated with the parameters addressed by the names of the treatments.

Table 1 List of finlet treatments labeled using the variable definitions presented in Fig. 1

Name	h_F (mm)	s_F (mm)	l_F (mm)	d_F/C
Baseline	0	∞	0	-
h2s4	2	4	65	0.9
h4s4	4	4	65	0.9
h6s4	6	4	65	0.9
h8s4	8	4	65	0.9
h6s6	6	6	65	0.9

A. Far-field Trailing Edge Noise

Figure 2 shows three representative beamforming maps at the center frequency of 1,060 Hz for the baseline, the h6s4 and the h6s6 treatment configurations, with the area of source integration marked with dashed lines. Analyzing these beamforming maps, it is found that for all configurations considered, the focus of the captured noise is perceptible as an isolated noise source expanding along the airfoil trailing edge. From a comparison of the results for the treated configurations with the baseline case, a net reduction in the noise emitted from the trailing edge region due to the presence of finlets can be clearly identified. At center frequencies higher than 2,000 Hz, additional noise emission from both the leading-edge and close to the side-walls becomes visible and care has been taken during the source integration to exclude these sources. Hence, a reduction of the trailing edge noise due to the application of finlets is clearly present as shown in Fig. 3. The SPL for the baseline configuration at different angles of attack suggests that at low frequencies of approximately 500 Hz, the far-field noise levels are comparable to each other and remain within the uncertainty range of 1.5 dB. Results for the h6s6 treatment at $\alpha_e = 0^\circ$ are cut at 3,000 Hz due to the presence of a high-frequency noise source, which leads to a notably higher SPL beyond 3,000 Hz.

In Fig. 3, the far-field SPL is shown for the baseline and the finlet-treated (referred to as treated hereafter) configurations, where the maximum reduction at each angle of attack considered is indicated for ease of reference.

Fig. 2 Representative beamforming contour maps at $\alpha_e = 0^\circ$ including airfoil outlines (solid lines) and the source integration area (dashed lines): (a) Baseline at $f_c = 1,060$ Hz, (b) h6s4 at $f_c = 1,060$ Hz and (c) h6s6 at $f_c = 1,060$ Hz.

Fig. 3 Far-field SPL for the baseline and treated configurations at various angles of attack: (a) $\alpha_e = 0^\circ$, (b) $\alpha_e = 2.3^\circ$, (c) $\alpha_e = 4^\circ$ and (d) $\alpha_e = 8^\circ$.

Figure 3a shows the far-field SPL determined from the beamforming array for the baseline and the treated configurations at an angle of attack of $\alpha_e = 0^\circ$. It can be observed that the application of finlets leads to a slight increase of the noise level at low frequencies of about 500 Hz by a maximum of 2 dB. However, at frequencies higher than 1,000 Hz, each finlet treatment demonstrates a notable noise reduction with a maximum reduction level of 6 dB at 1,500 Hz for both the h6s4 and the h8s4 treatments compared to the baseline. For higher angles of attack, $\alpha_e = 2.3^\circ$ and 4° , shown in Figs. 3b and 3c, respectively, a consistent trend can be identified. The h6s4 and the h8s4 treatments are most effective in terms of reducing the trailing edge noise at relatively high frequencies, whereas the h2s4 finlet treatment remains the least effective. When the angle of attack increases to $\alpha_e = 8^\circ$, as shown in Fig. 3d, the majority of the finlets no longer show any noise reduction across the range of frequencies considered. However, the highest treatment, h8s4, is still able to reduce the trailing edge noise consistently by approximately 2 dB across the frequency range. Considering that the boundary layer thickness, δ , generally grows with increasing angle of attack, the noise reduction for the h8s4 finlets suggests that there is a correlation between the ratio of the finlet height to the boundary layer thickness and the finlets' ability to reduce the trailing edge noise. As the finlets are designed to influence the characteristics of the turbulent boundary layer, angles of attack above $\alpha_e = 8^\circ$ are not examined in the study since the boundary layer separates from

the airfoil surface at higher angles [32].

A closer examination of the results for $\alpha_e \leq 4^\circ$ further reveals that there may exist an optimal ratio between the finlet height and the turbulent boundary layer thickness. A clear trend of increasing effectiveness in reducing the trailing edge noise can be observed when the finlet height increases from $h_F = 0$ mm (i.e. the baseline configuration) to $h_F = 6$ mm. Nevertheless, further increasing the finlet height to 8 mm does not bring about further benefits, with finlets with $h_F = 6$ mm performing slightly better at higher frequencies.

When the finlet spacing, s_F , increases from 4 mm to 6 mm, i.e. comparing the h6s4 and the h6s6 treatment with each other in Figs. 3a to 3d, it can be seen that the effectiveness of trailing edge noise reduction of the finlets deteriorates. The far-field sound pressure level is up to 3 dB lower for the h6s4 treatment compared to the h6s6 counterpart, except at $\alpha_e = 8^\circ$ where the h6s6 treatment performs better than the h6s4 treatment at frequencies below 1,000 Hz. This observation suggests that enhanced interaction between the boundary layer and the wall structures of the finlets is beneficial to mitigating the trailing edge noise of the airfoil.

B. Boundary Layer Velocity Profiles

Since the finlets are expected to modify the flow characteristics of the turbulent boundary layer past the airfoil, examining the turbulent boundary layer velocity profiles of the NACA 0012 airfoil helps identify the aerodynamic effects of the finlets and thus allowing an optimal choice of finlet parameters. The boundary layer usually grows along the chord of the airfoil, reaching its maximum extent at the trailing edge, which is also the position most relevant to trailing edge noise [4]. In order to quantify the correlation between the ratio of finlet height, h_F , to boundary layer thickness of the baseline configuration, δ , and the ability of the finlets to reduce the trailing edge noise, the boundary layer velocity profiles on the airfoil suction side at the trailing edge, $x/C = 0.99$ are examined. Here, the boundary layer thickness is determined as the distance from the airfoil surface at which the streamwise velocity, u , reaches 95 % of the velocity of the irrotational flow just outside the boundary layer, U_e , and is thus referred to as $\delta_{0.95}$. Similar definitions of the boundary layer thickness were used for example in [2, 20, 30, 40]. The origin of the y -axis in Fig. 4 designates the airfoil surface instead of the profile center line.

Figures 4a and 4b show the boundary layer velocity profiles of the baseline configuration and the h6s4 treatment at two different angles of attack $\alpha_e = 0^\circ$ and 4° , respectively. The velocity distributions presented show a decreased velocity close to the airfoil surface for the h6s4 compared to the baseline configuration and an almost linear gradient in the lower half of the boundary layer. Both features indicate that the finlet treatment likely modifies the linear region in the boundary layer [41], which is yet to fully recover at the trailing edge. Recall from the far-field noise measurements that the h6s4 treatment has been found to attain the largest trailing edge noise reduction across the frequency range considered for angles of attack of $\alpha_e \leq 4^\circ$. Thus, its ratio of finlet height to the boundary layer thickness of the baseline at the trailing edge is considered close to the optimal configuration. However, at $\alpha_e = 8^\circ$, the higher h8s4 treatment is

seen to reduce the trailing edge noise more effectively than the other finlets, outperforming the h6s4 treatment. Hence, it is possible to roughly deduce an optimal ratio from the relation of these two finlet heights to the boundary layer thickness at different angles of attack under the present experimental conditions. From Figs. 4a and 4b, it can be observed that the boundary layer grows from $\delta_{0.95} = 8.3$ mm at $\alpha_e = 0^\circ$ to 9.8 mm at 4° from the present measurement, and continues to grow to approximately $\delta_{0.95} = 11.3$ mm at $\alpha_e = 8^\circ$. Note that the boundary layer thickness at $\alpha_e = 8^\circ$, though not shown here, has been extracted directly from Mayer *et al.* [32], where both experiments were conducted at similar free-stream conditions with the same airfoil. For the h6s4 treatment, the ratios of $h_F/\delta_{0.95}$ are 0.72, 0.61 and 0.53 for the angles of attack, $\alpha_e = 0^\circ$, 4° and 8° , respectively, whereas for the h8s4 treatment, the ratios become 0.96, 0.81 and 0.7 with increasing angles of attack. From the far-field results in Figs. 3a to 3c, the h6s4 treatment is observed to perform generally better than the h8s4 treatment at $\alpha_e \leq 4^\circ$, whereas the h8s4 treatment shows more significant noise reduction at $\alpha_e = 8^\circ$. Furthermore, the effectiveness of the h6s4 treatment of reducing the trailing edge noise decreases with increasing angle of attack. This is manifested through the ‘crossover’ frequency, at which the h6s4 treatment achieves a higher magnitude of noise reduction than the h8s4 treatment at $\alpha_e \leq 4^\circ$. For instance, this frequency shifts from approximately 1,750 Hz at $\alpha_e = 2.3^\circ$ to 1,900 Hz at $\alpha_e = 4^\circ$, meaning that the h8s4 treatment outperforms the h6s4 counterpart over a wider frequency range as the angle of attack increases. Therefore, it can be deduced that under the given experimental condition, the optimal ratio of the finlet height to the boundary layer thickness of the baseline at the trailing edge is $h_F/\delta_{0.95} \approx 0.7$, i.e. the effectiveness of finlet treatments increases as the ratio approaches 0.7. Hence, a decrease in reduction by the h6s4 and an increase in reduction by the h8s4 treatment with a growing turbulent boundary layer thickness is observed. It should be noted that since the boundary layer thickness is measured at a single position close to the trailing edge and the finlet-treated area is further upstream, the result of the optimal finlet height to boundary layer thickness ratio may vary for airfoils of different chord lengths or if the measurement of the boundary layer velocity profile is moved further upstream. The investigations of Mayer [29] show that the boundary layer thickness on the NACA 0012 airfoil in the absence of flow separation at $x/C = 0.93$ is up to 20 % lower than at $x/C = 0.98$, which has to be considered when determining the most effective finlet height for a certain configuration.

The profiles of the root-mean-square of the velocity fluctuations, u'_{rms} , close to the trailing edge at $\alpha_e = 0^\circ$ and 4° , presented in Figs. 4c and 4d for the h6s4 treatment and the baseline configuration, shed light on the turbulence intensity within the boundary layer. With y normalized by the finlet height, h_F , and u'_{rms} normalized by the free-stream velocity, U_∞ , the localized level of high turbulence intensity can be identified. As also reported by Mayer *et al.* [32], the turbulence fluctuation for the baseline configuration is highest near the airfoil surface for $\alpha_e = 0^\circ$ and peaks at a small distance above the surface for $\alpha_e = 4^\circ$. For the treated configurations at both angles of attack considered, two significant changes to the u'_{rms} profile due to the finlets are observed. Firstly, the maximum turbulence intensity increases from $u'_{\text{rms}}/U_\infty = 0.093$ to $u'_{\text{rms}}/U_\infty = 0.097$ for $\alpha_e = 0^\circ$ and from $u'_{\text{rms}}/U_\infty = 0.09$ to $u'_{\text{rms}}/U_\infty = 0.097$ for $\alpha_e = 4^\circ$. Secondly, the turbulence intensity peaks occur at larger distances away from the airfoil surface, i.e. at $y/h_F = 0.3$ instead

Fig. 4 Streamwise velocity profiles for the baseline and the h6s4 configuration at $x/C = 0.99$: Boundary layer profiles for (a) $\alpha_e = 0^\circ$ and (b) $\alpha_e = 4^\circ$, root-mean-square velocity profiles for (c) $\alpha_e = 0^\circ$ and (d) $\alpha_e = 4^\circ$.

of $y/h_F = 0.1$ for $\alpha_e = 0^\circ$ and at $y/h_F = 0.5$ instead of $y/h_F = 0.4$ for $\alpha_e = 4^\circ$. At the same time, the turbulence intensity closest to the airfoil surface reduces slightly for both $\alpha_e = 0^\circ$ and 4° . The first observation is believed to be associated with a shear layer forming on top of the finlet treatments, as described by Afshari *et al.* [21]. Subsequently, the eddies in the shear layer must be convected downstream from the treated area toward the airfoil trailing edge. The second observation is likely due to a combined effect of the lift of turbulence eddies away from the airfoil trailing edge as previously described by Bodling and Sharma [23] and Clark *et al.* [19], as well as the enhanced dissipation through the finlet walls. The boundary layer velocity measurements suggest that the boundary layer at the trailing edge of the finlet-treated airfoil experiences a decrease of flow velocity and turbulence intensity very close to the airfoil surface, and conversely, an increase of peak turbulence intensity further away from the surface.

C. Static Pressure Field

Changes in the boundary layer, such as boundary layer separation and flow recirculation, occur when there is a strong adverse pressure gradient. The pressure coefficient distribution along airfoil chord is thus an indicator for whether the flow is likely to remain attached or undergoes separation at a certain chord position. In order to better understand

the flow development past the treated airfoil, the static pressure distribution and its fluctuation are thus recorded and examined. Fig. 5 presents the pressure coefficient, C_p , for the angles of attack of $0^\circ \leq \alpha_e \leq 8^\circ$ and a range of finlet treatments including h2s4, h6s4, h8s4 and h6s6. As shown in Fig. 5a, the pressure of both the suction and pressure side of the baseline airfoil coincides well at $\alpha_e = 0^\circ$, signifying that the angle of attack has been correctly adjusted to zero at the start of the experiment. From Figs. 5b to 5d, it can be observed how the difference in pressure coefficient between the two sides of the airfoil grows as the angle of attack varies from $\alpha_e = 0^\circ$ to 8° . In each case, the effect of the turbulator trip is visible shortly downstream of $x/C = 0.1$.

As can be observed in Fig. 5, the pressure coefficients measured for the treated airfoil do not differ substantially from those of the baseline configuration, showing that the finlet treatments have a limited impact on the static pressure distribution of the airfoil. This means that the treatments also have very minor influence on the total pressure drag of the airfoil. Upon closer examination, a noticeably stronger adverse pressure gradient exists upstream of the treated area (highlighted in grey in Fig. 5) for the treated airfoil when compared to the baseline, on both sides of the airfoil and for all α_e considered. On the suction side, an increase of the static pressure coefficient is observable from $x/C \approx 0.4$

Fig. 5 Pressure coefficient distribution for the baseline (—), the h2s4 (—△—), the h6s4 (—○—), the h8s4 (—□—) and the h6s6 (·····◇·····) treatment: (a) $\alpha_e = 0^\circ$, (b) $\alpha_e = 2.3^\circ$, (c) $\alpha_e = 4^\circ$ and (d) $\alpha_e = 8^\circ$.

Fig. 6 Distribution of the root-mean-square of the fluctuations of the pressure coefficients around their mean for the baseline (—), the h2s4 (—△—), the h6s4 (—○—), the h8s4 (—□—) and the h6s6 (···◇···) treatment: (a) $\alpha_e = 0^\circ$, (b) $\alpha_e = 2.3^\circ$, (c) $\alpha_e = 4^\circ$ and (d) $\alpha_e = 8^\circ$.

until immediately upstream of the treated area, giving rise to a greater adverse pressure gradient. An adverse pressure gradient upstream of the finlets indicates a resistance to the flow from the finlet leading edges, which can also be observed in a greater extent from experimental investigations on forward facing steps [42, 43]. In contrast, when the flow enters the treated area, the static pressure coefficient on both the suction and pressure side decreases. Note that since the pressure coefficient is negative on the suction side, a decrease means a more negative level, i.e. its magnitude increases. Moving further toward the trailing edge, the pressure coefficient of the treated airfoil becomes slightly lower than for the baseline configuration on both sides.

The root-mean-square of the fluctuations of the pressure coefficients, $C_{p,rms}$, around their mean value at each position can also be indicative of the turbulence intensity on the airfoil surface. Lower levels of $C_{p,rms}$ suggest lower turbulence levels, whereas higher levels, especially local extrema, can be a sign of the formation of large turbulence structures, for example through vortex shedding or boundary layer separation [42, 43]. In Fig. 6, the distribution of $C_{p,rms}$ along the airfoil chord is presented for the angles of attack of $\alpha_e = 0^\circ$ to 8° , respectively. Again, the effects of the turbulator trip can be clearly identified shortly downstream of $x/C \approx 0.1$ as a local maximum for both the baseline

and treated configurations. It can be observed for all angles of attack considered that the finlet treatments lead to a reduction of the static pressure fluctuations up to about the front third of the airfoil. On the other hand, within the treated area, a slightly heightened fluctuation level can be identified. Hence, it may be inferred from the $C_{p, \text{rms}}$ results that the presence of a finlet treatment possibly lowers the turbulence level upstream of the treated area but intensifies it within the treated area. However, it should be cautioned that the lowered turbulence observed upstream of the finlets from the $C_{p, \text{rms}}$ results could also be due to the additional uncertainties during the measurement process. As seen from the static pressure results, the pressure coefficient distribution and the fluctuation level within the treated area differ noticeably from those of the baseline configuration, and hence it is useful to further investigate the pressure and velocity fields within the treated area.

D. Auto-correlations of Unsteady Surface Pressure

By examining the unsteady surface pressure, it is possible to correlate the velocity fields with the dynamics of the surface pressure, in order to both confirm the observations from the velocity measurements and further analyze the effects of finlets on the flow. To focus on the streamwise flow development, results from the unsteady pressure field are presented for multiple chordwise measurement locations, from upstream of the finlets to the trailing edge, with a single angle of attack, $\alpha_e = 4^\circ$. The analysis of data for other angles of attack is omitted for the sake of brevity, since they exhibit similar trends as $\alpha_e = 4^\circ$. Figures 7 and 8 show the normalized auto-correlation coefficient distribution from the unsteady surface pressure measurements, R_{pp} , along the airfoil chord. The signals are high-pass filtered with a pass-band frequency of 20 Hz to remove low frequency signal noises.

From the auto-correlation results of the baseline configuration, shown in Figs. 7a to 7f, some important information on the boundary layer characteristics of the untreated (baseline) NACA 0012 airfoil can be obtained. At all measurement locations from $x/C = 0.63$ to 0.93, a high initial rate of decay of the auto-correlation function is observed, decreasing slightly from the most upstream location toward the trailing edge. Moreover, the overall width of the auto-correlation peak, defined as the time lag it takes for the auto-correlation function to settle to zero [2], increases toward the trailing edge. Since the overall width of the auto-correlation function is a measure of the time scale associated with the largest turbulence structures in the flow [2], this means that the turbulence structures in the boundary layer grow in size as being convected downstream. In order to quantify the overall width and hence the time scale associated with the turbulence structures, the integral time scale, $\mathcal{T}$, can be obtained by integrating the magnitude of the auto-correlation coefficients over the time lag [2] as:

$$\mathcal{T} = \int_0^\infty R_{pp}(\tau) d\tau \approx \int_0^{\tau_0} R_{pp}(\tau) d\tau. \quad (5)$$

Here, τ designates the time lag at which the correlation is measured. Since the duration of the sampling has to be finite,

the integration is limited to a time lag, τ_0 , for which the absolute value of the auto-correlation coefficient becomes less than 0.0005 and its gradient becomes less than 0.005, i.e., $|R_{pp}| < 0.0005$ and $\frac{dR_{pp}}{d\tau} < 0.005$ [44].

Having defined some aspects of the auto-correlation functions, the differences between the baseline and the treated configurations slightly upstream, within and downstream of the finlet-treated area, as shown in Fig. 7, can now be discussed. From Fig. 7a, it can be seen that the flow upstream of the treated area is not significantly perturbed by any of

Fig. 7 Non-dimensional pressure auto-correlation coefficients for the baseline and the treated configurations at $\alpha_e = 4^\circ$: (a) $x/C = 0.63$, (b) $x/C = 0.75$, (c) $x/C = 0.82$, (d) $x/C = 0.87$, (e) $x/C = 0.9$ and (f) $x/C = 0.93$.

the treatments, as all the pressure auto-correlation coefficients almost coincide with each other. The integral time scale at $x/C = 0.63$, calculated from Eq. (5), is approximately $\mathcal{T}U_\infty/C = 0.005$. The auto-correlation peak significantly broadens close to the entrance of the finlet treatments as observed in Fig. 7b, which suggests a possible formation of large-scale turbulence structures at the front part of the treatments. The integral time scale is observed to increase with increasing finlet height, h_F , and decrease with increasing finlet spacing, s_F . As the measurement location moves further downstream within the finlet-treated area, the integral time scale experiences first a decrease in the middle of the treated area (Fig. 7c), followed by another increase toward the end of the finlet treatments (Fig. 7d). Yet, a more significant widening of the auto-correlation coefficient, R_{pp} , can be clearly observed at a small distance downstream of the treated area at $x/C = 0.93$ for the h6s4 and h8s4 finlet treatments, as seen in Fig. 7f. The integral time scales for the h6s4 and the h8s4 treatment at this location are $\mathcal{T}U_\infty/C = 0.03$ and $\mathcal{T}U_\infty/C = 0.02$, respectively, whereas the time scales for the other configurations are roughly $\mathcal{T}U_\infty/C = 0.01$. The widening of the auto-correlation peaks indicates a strong interaction between the flow through the finlet channels and the shear layers produced along the finlet wall structures [21]. Indeed, investigating various finlet treatments on a flat plate, Afshari *et al.* [21] reported the emergence of a free shear layer in the wake of the finlets, even causing a region of recirculation close to the finlet trailing edges. Recall that these two finlet treatments produce the most effective trailing edge noise reduction in the frequency range considered, thus, such flow interaction is likely to be beneficial to the reduction of trailing edge noise.

Figure 8 shows the auto-correlation coefficient results, R_{pp} , for the h6s4 treatment as a contour plot across $0.5 < x/C < 0.95$, in contrast to the baseline configuration, at an angle of attack of $\alpha_e = 4^\circ$. The zero auto-correlation transition, i.e. the time lag for which the auto-correlation coefficient first passes zero magnitude, is indicated with a white line in each case, allowing an easy estimate of the auto-correlation peak width. The contour for the baseline configuration shown in Fig. 8a illustrates how the auto-correlation coefficient continuously widens from the mid chord toward the trailing edge of the NACA 0012 airfoil as the turbulent boundary layer develops along the airfoil chord [32].

Fig. 8 Non-dimensional pressure auto-correlation coefficient contours at $\alpha_e = 4^\circ$: (a) Baseline configuration and (b) Airfoil treated with h6s4 finlets.

The auto-correlation coefficient contour for the h6s4 treatment, shown in Fig. 8b, confirms that the impact of the finlet treatments does not become visible until immediately upstream of the treated area. The possible formation of large-scale turbulence structures, as indicated by the widening of the auto-correlation peak width, can be discerned from the finlet leading edges onward up to about $x/C = 0.74$, which is also corroborated by the slight increase in the pressure gradient upstream of this region (see Fig. 5c). Moreover, the variations of the auto-correlation peak width within the treated area and the significant increase further downstream after the flow exits the finlet treatments can be clearly observed. It is worth mentioning that transitioning from the finlet exit to the wake region, i.e. at $x/C = 0.9$, the zero transition time lag decreases to a local minimum, whereas the overall auto-correlation peak width, and thus the integral time scale of the largest turbulence, remains comparable to that within the treated area at $x/C = 0.87$.

E. Unsteady Surface Pressure Spectra

From Amiet's theory [4], it is known that the far-field trailing edge noise is directly related to the surface pressure fluctuation PSD, ϕ_{pp} , at the trailing edge. Figure 9 shows the development of ϕ_{pp} along the airfoil chord. Upstream of the treated area, the finlet treatments have almost no impact on the unsteady surface pressure fluctuations as seen in Fig. 9a at $x/C = 0.63$, agreeing well with the pressure auto-correlation results. However, the PSD levels of the unsteady surface pressure begin to rise gradually at lower frequencies as the flow is convected further downstream through the finlets. At $x/C = 0.93$, the measurement location closest to the trailing edge as shown in Fig. 9f, all finlet treatments exhibit noticeably higher levels of the unsteady surface pressure spectra than the baseline configuration below 2,000 Hz. Such an increase of energy contents at low to medium frequencies can be attributed to the formation of relatively large-scale turbulence structures with the presence of finlets. More importantly, in contrast to the elevated levels at lower frequencies, the PSD levels of the unsteady surface pressure at higher frequencies, i.e. $2,000 \text{ Hz} < f < 10,000 \text{ Hz}$, can be observed to drop below that of the baseline, starting from the rear part of the treated area (see Fig. 9d to 9f). As the measurement location moves toward the end of the treated area, the difference between the unsteady surface pressure spectra of the finlet and the baseline configurations widens at higher frequencies, which is likely due to the enhanced dissipation of small-scale turbulence with the finlet wall structures (i.e. larger wetted area).

A closer examination reveals that the reduction of the PSD levels at higher frequencies is notably accelerated after the flow exits the finlet treatments for the h6s4 and h8s4 treatments, reaching approximately 12 dB Hz^{-1} and 10 dB Hz^{-1} reduction across the frequency range of $4,000 \text{ Hz} < f < 7,000 \text{ Hz}$, respectively. This reaffirms the observation from the pressure auto-correlation function that the flow interactions between the flow being channeled through the finlet treatment and that of the shear layers formed by the finlet wall structures (Afshari *et al.* [21]) can produce beneficial effects on the unsteady surface pressure fluctuations, and placing the finlets at some distance upstream of the trailing edge allows the flow interaction and its benefits to fully develop.

It is now useful to zoom in to the unsteady surface pressure spectra measured closest to the trailing edge at

Fig. 9 Surface pressure fluctuation PSD for the baseline and the treated configurations at $\alpha_e = 4^\circ$: (a) $x/C = 0.63$, (b) $x/C = 0.75$, (c) $x/C = 0.82$, (d) $x/C = 0.87$, (e) $x/C = 0.9$ and (f) $x/C = 0.93$.

$x/C = 0.93$, as shown in Fig. 9f, in order to relate the near-field pressure fluctuation results to the radiated far-field noise. Based on the unsteady surface pressure fluctuation results, it is expected that the far-field noise shows some levels of increase at lower frequencies and conversely, even more decrease at higher frequencies. The far-field sound pressure levels, shown in Fig. 3c, correspond generally well with the near-field unsteady surface pressure spectra. Taking the h6s4 treatment as an example, the ‘cross-over’ frequency, at which its unsteady surface pressure PSD changes from

higher to lower than the baseline configuration, is approximately 1,200 Hz and its corresponding far-field noise result begins to show significant attenuation at approximately 1,000 Hz. In fact, the near-field unsteady surface pressure PSD shows a general reduction beyond 1,000 Hz for all finlets compared to the baseline configuration and so does the far-field sound pressure level. Comparing the h6s4 and h8s4 treatments, while the h6s4 treatment is more effective in reducing the trailing edge noise at frequencies higher than 2,000 Hz, the h8s4 treatment tends to suppress the noise increase at lower frequencies better, which both agree very well with their respective unsteady surface pressure spectra. It is worthwhile to mention at this point that due to the near-field surface pressure PSD increase observed for the treated configurations, an increase of radiated far-field noise at frequencies below 500 Hz (i.e. the limit of the present far-field measurement frequency) is also plausible. However, the unsteady surface pressure spectra for the treated configurations show that the increase of surface pressure PSD at lower frequencies is notably less pronounced than the decrease over the high frequency range. Hence, it can be inferred from the near-field surface pressure PSD results that the finlets may increase the noise at frequencies below 500 Hz, but nevertheless the absolute increase will be smaller than the noise decrease at higher frequencies of 1,000 Hz to 4,000 Hz. As a measure for the overall viability of the finlets to reduce noise between $60 \text{ Hz} \leq f \leq 5,000 \text{ Hz}$, the unsteady surface pressure fluctuation spectra at $x/C = 0.99$ for the different treated configurations and the baseline were integrated over the frequency range valid for the remote sensing transducers. The surface pressure PSD has not been included here for the sake of brevity, however the overall trend follows the behavior observed for the pressure transducer at $x/C = 0.93$, as shown in Fig. 9f. The results show that compared to the baseline case the h2s4, the h4s4 and the h8s4 treatment increase the overall surface pressure fluctuation intensity by approximately 29 %, 8 % and 5 %, respectively, due to the increase in PSD at low frequencies, whereas the application of the h6s4 and the h6s6 treatment lead to an overall reduction of up to 5 % and 2 %, respectively.

F. Cross-correlations of Unsteady Surface Pressure

To gain more knowledge on where the significant changes of the boundary layer flow characteristics take place, the cross-correlations of the unsteady surface pressure at different chordwise locations are investigated. Moreover, by examining the cross-correlations of the unsteady surface pressure fluctuations between different measurement locations, the convection velocity of the turbulent boundary layer can be determined, assuming Taylor's frozen turbulence hypothesis [2]. Figure 10 depicts the cross-correlation coefficients, $R_{p_i p_j}$, for the baseline configuration and the finlet treatments as functions of the time lag, τ , between two measurement locations, x_i and x_j , normalized by the free-stream velocity, U_∞ , and the airfoil chord, C . Since all the configurations with different angles of attack show the same trends, only results for a single angle of attack, $\alpha_e = 4^\circ$, are presented. The time lag of the maximum correlation between the measurements at the two positions x_i and x_j is denoted as τ_m .

Upstream of the treated area, as shown in Fig. 10a, the pressure cross-correlation coefficients, $R_{p_i p_j}$, for the baseline and the treated configurations are largely comparable to each other in terms of the amplitude and time lag, τ_m . However,

Fig. 10 Pressure cross-correlation coefficients, $R_{p_i p_j}$, between the signals of two transducers at x_i and x_j for the baseline and the treated configurations at $\alpha_e = 4^\circ$: (a) $x_i/C = 0.633$ and $x_j/C = 0.666$, (b) $x_i/C = 0.699$ and $x_j/C = 0.716$, (c) $x_i/C = 0.833$ and $x_j/C = 0.866$, (d) $x_i/C = 0.866$ and $x_j/C = 0.899$, (e) $x_i/C = 0.899$ and $x_j/C = 0.933$ and (f) $x_i/C = 0.933$ and $x_j/C = 0.966$.

a second peak with a larger time lag is captured immediately after the flow enters the treated area for both the h4s4 and the h6s4 treatment (see Fig. 10b). For ease of reference, the time lag associated with the primary cross-correlation peak is denoted as $\tau_{m,1}$, whereas the time lag for the secondary peak is designated as $\tau_{m,2}$ in the following discussion. The emergence of a secondary cross-correlation peak at $\tau_{m,2}$ corroborates that the boundary layer flow undergoes

considerable changes with some large-scale turbulence structures forming at the front part of the finlet treatments, which has also been observed from the widening of the auto-correlation coefficient and the low-frequency increase of the unsteady surface pressure spectra. On the other hand, finlet treatments with smaller finlet height such as h2s4, and with larger finlet spacing, such as h6s6, show limited changes compared to the baseline configuration. Recall that these finlet treatments experience a milder increase of the unsteady surface pressure spectra at low frequencies and thus, any modification to the flow by the presence of finlets is also likely to be limited. The absence of the secondary peak for finlet treatments with small height or large spacing indicates that the double-peak characteristics of the pressure cross-correlation relates to the flow interaction with the finlet wall-structures. Interestingly, the h8s4 treatment, which is effective in reducing the trailing edge noise, shows a notably wider primary cross-correlation peak instead of a second one, clearly illustrating the effect of the finlet height on the dynamics of the flow convected through the finlets. The double-peak characteristics shown by the h4s4 and h6s4 treatments disappear as the finlets reach their maximum height. Hence, the difference in convection velocity between the two structures observed in Fig. 10b can possibly be explained with the difference in the distance the two distinct flow structures have to cover from one pressure transducer location to the next, because the large-scale turbulence structures associated with the finlet walls are likely convected along the finlet ridges.

Figures 10d and 10e depict the cross-correlation coefficients as the flow passes from the treated area into the finlet wake. At these locations, not only a second correlation peak emerges with a noticeably larger time lag, $\tau_{m,2}$, but the time lag associated with the primary correlation peak, $\tau_{m,1}$, also grows for all finlet treatments as compared to the baseline configuration. It is reasonable to assume that the former can be attributed to the interaction between the flow being channeled through the spaces between the finlets and the flow of the shear layers along the finlet wall structures, while the latter indicates a difference in the streamwise convection velocity, which will be further explained in section III.G below. Similar to the results observed upstream at the front part of the finlets, the difference in convection velocity can possibly be attributed to the different distances which these turbulence structures need to travel from one transducer location to another when they merge (i.e. the shear layers descend to merge with the channeled flow). As the finlet wake develops further toward the trailing edge, the merged flow produces one single correlation peak again, as shown in Fig. 10f.

G. Streamwise Convection Velocity and Length Scale

Based on the cross-correlation coefficient results, the mean convection velocity, U_c , of the boundary layer flow can be estimated by $U_c = \Delta x / \tau_m$, where Δx is the separation distance between two measurement locations at x_i and x_j , and τ_m denotes the time lag of the maximum correlation peak. Since there exist two correlation peaks for some finlet treatments at different measurement locations (see Fig. 10), the convection velocity is always evaluated using the first correlation peak, $\tau_{m,1}$, in order to represent the bulk flow convection velocity rather than the large-scale turbulence

structures formed due to the finlets. Figure 11 shows the evolution of the convection velocity, U_c , from slightly upstream of the treated area to the finlet wake along the airfoil chord. It can be observed that firstly the convection velocity decreases consistently along the airfoil chord from approximately $U_c/U_\infty = 0.85$ to $U_c/U_\infty = 0.6$ and secondly the convection velocity of the flow through the finlet treatments essentially reduces below and remains slower than that of the baseline configuration from the middle of the treated area to the trailing edge.

Taking a step further from the mean convection velocity, the largest turbulence length scale, Λ_x , in the x -direction (i.e. streamwise) can be determined as [2]

$$\Lambda_x = U_c \mathcal{T}, \quad (6)$$

Fig. 11 Convection velocity distribution along the airfoil chord for the baseline and the treated configurations at $\alpha_e = 4^\circ$.

Fig. 12 Distribution of the streamwise length scale of the largest turbulence along the airfoil chord for the baseline and the treated configurations at $\alpha_e = 4^\circ$.

where U_c is the convection velocity determined as described above and $\mathcal{T}$ is the integral time scale of the largest turbulence discussed in Section III.D. Since the finlet treatments do not seem to alter the spanwise correlation length, Λ_z , significantly [24], the variations of the largest turbulence length scales are expected to take place mainly along the x - and the y -direction with the application of finlet treatments. Figure 12 shows the development of the streamwise turbulence length scale, Λ_x , normalized by the boundary layer thickness of the baseline at the trailing edge, $\delta_{0.95}$, along the airfoil chord in front of, within and downstream of the treated area. Upstream of the finlet treatments, at $x/C = 0.65$, a slight increase of the largest turbulence length scale for each finlet treatment compared to the baseline configuration can be identified. Consistent with the results of the unsteady surface pressure fluctuations, the difference between the treatments to each other and the baseline configuration becomes increasingly evident within the treated area. As already observed from the pressure auto-correlation results, the streamwise turbulence length scale increases sharply at the leading edge of all finlet treatments considered in the study, except for the h2s4 and the h6s6 treatment, which have the lowest wall height and the widest finlet spacing, respectively, indicating the formation of large-scale turbulence structures as the flow interacts with the finlet wall structures. It is observed within the treated area from $x/C = 0.71$ to $x/C = 0.75$ that the length scale associated with the turbulence structures forming at the front of the finlets grows with increasing finlet height and reduces with increasing finlet spacing. In other words, for the finlets with larger finlet heights, the turbulence length scale is greater than that for lower finlets. Moreover, finlets with a large spacing have turbulence length scales comparable with the baseline configuration in x -direction. A similar trend is observed further downstream within the treated area at $x/C = 0.83$, however, the largest turbulence length scale shows a clear decrease compared to the upstream measurement location. This observation indicates that the influence of the large-scale turbulence structures forming in the front part of the finlets diminishes as the flow is convected downstream. Bodling and Sharma [23] suggested from their simulation results that some of these flow structures may have been lifted above the finlet channels. In the wake of the finlet treatments at $x/C = 0.92$, the largest turbulence length scale grows again. It can be seen from the results shown in Fig. 12 that the growth of the length scales, Λ_x , from $x/C = 0.83$ to $x/C = 0.92$ for the h2s4, h4s4 and h6s6 treatments (i.e. treatments with lower finlet heights or larger finlet spacing which are less effective in reducing the trailing edge noise), is comparable to the growth of the baseline configuration of approximately $0.07 \delta_{0.95}$ or 0.7 mm. In contrast, the h6s4 and the h8s4 treatment show a much more significant growth of the length scale of more than $0.23 \delta_{0.95}$ or 2.3 mm and thus are likely to induce changes to the flow significantly beneficial to the reduction of the unsteady surface pressure fluctuations and thus, leading to attenuation of the airfoil trailing edge noise.

IV. Conclusions

The effectiveness of finlets in reducing the airfoil trailing edge noise has been experimentally studied at a moderate Reynolds number of 400,000. The far-field sound pressure levels of the trailing edge noise of a NACA 0012 airfoil have

been measured for different finlet treatments applied on both sides of the airfoil at a distance of $d_F = 0.9C$ from the airfoil leading edge and compared with the untreated (baseline) configuration. It is observed that finlets can effectively reduce the far-field trailing edge noise in the frequency range from 1,000 Hz to 4,000 Hz by up to 6 dB, whereas a potential noise increase below the frequency limit of the far-field measurements (i.e. 500 Hz) is expected due to the observed increase in surface pressure PSD at the trailing edge. From the far-field noise and boundary layer velocity measurements, a relation between the ratio of finlet height, h_F , to boundary layer thickness, δ , and the effectiveness of the finlets to reduce trailing edge noise can be established with an optimal ratio of $h_F/\delta_{0.95} \approx 0.7$ for the present experimental condition.

The noise reduction mechanism of the finlets has been further examined using static and unsteady surface pressure measurements. In particular, the study has focused on the development of the velocity and pressure field within and downstream of the treated area, i.e. measurements in between and in the wake of the finlets. The reduction of the far-field trailing edge noise is observed to directly relate to the decrease of the unsteady surface pressure fluctuations at frequencies higher than 1,000 Hz, setting in downstream of the treated area and ranging to the trailing edge of the airfoil. From the auto- and cross-correlation of the unsteady surface pressure it is seen that the decrease of high-frequency surface pressure fluctuations can possibly be attributed to the additional viscous dissipation introduced by the finlet wall structures as well as the formation of large-scale turbulence structures when the flow enters and exits the finlet channels, and the subsequent mixing of these large-scale structures with the boundary layer. Moreover, the streamwise turbulence length scales show that the turbulence structures undergo notable stretching with the presence of finlets, which could also lead to the observed increase at low frequencies and decrease at high frequencies of the unsteady surface pressure fluctuations, respectively.

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References

- [1] Lockard, D. P., and Lilley, G. M., “The airframe noise reduction challenge,” Tech. Mem. TM-2004-213013, NASA, Langley Research Center, Hampton, Virginia, 2004.
- [2] Glegg, S., and Devenport, W., *Aeroacoustics of Low Mach Number Flows*, Academic Press, 2017.
- [3] Brooks, T. F., Pope, D., and Marcolini, M. A., “Airfoil self-noise and prediction,” Reference Publication 1218, NASA, Langley Research Center, Hampton, Virginia, 1989.

- [4] Amiet, R. K., "Noise due to turbulent flow past a trailing edge," *Journal of Sound and Vibration*, Vol. 47, No. 3, 1976, pp. 387–393. [https://doi.org/10.1016/0022-460X\(76\)90948-2](https://doi.org/10.1016/0022-460X(76)90948-2).
- [5] Szőke, M., Fisaletti, D., and Azarpeyvand, M., "Effect of inclined transverse jets on trailing-edge noise generation," *Physics of Fluids*, Vol. 30, No. 8, 085110, 2018. <https://doi.org/10.1063/1.5044380>.
- [6] Leitch, T. A., Saunders, C. A., and Ng, W. F., "Reduction of unsteady stator-rotor interaction using trailing edge blowing," *Journal of Sound and Vibration*, Vol. 235, No. 2, 2000, pp. 235–245. <https://doi.org/10.1006/jsvi.2000.2922>.
- [7] Szőke, M., Fisaletti, D., and Azarpeyvand, M., "Influence of boundary layer flow suction on trailing edge noise generation," *Journal of Sound and Vibration*, Vol. 475, 11527, 2020. <https://doi.org/10.1016/j.jsv.2020.115276>.
- [8] Wolf, A., Lutz, T., Würz, W., Krämer, E., Stalnov, O., and Seifert, A., "Trailing edge noise reduction of wind turbine blades by active flow control," *Wind Energy*, Vol. 18, No. 5, 2015, pp. 909–923. <https://doi.org/10.1002/we.1737>.
- [9] Lilley, G. M., "A study of the silent flight of the owl," *4th AIAA/CEAS Aeroacoustics Conference*, Toulouse, France, 1998, p. 2340. <https://doi.org/10.2514/6.1998-2340>.
- [10] Azarpeyvand, M., Gruber, M., and Joseph, P. F., "An analytical investigation of trailing edge noise reduction using novel serrations," *19th AIAA/CEAS Aeroacoustics Conference*, Berlin, Germany, 2013, p. 2009. <https://doi.org/10.2514/6.2013-2009>.
- [11] Chong, T. P., and Vathylakis, A., "On the aeroacoustic and flow structures developed on a flat plate with a serrated sawtooth trailing edge," *Journal of Sound and Vibration*, Vol. 354, 2015, pp. 65–90. <https://doi.org/10.1016/j.jsv.2015.05.019>.
- [12] Lyu, B., Azarpeyvand, M., and Sinayoko, S., "Prediction of noise from serrated trailing edges," *Journal of Fluid Mechanics*, Vol. 793, 2016, pp. 556–588. <https://doi.org/10.1017/jfm.2016.132>.
- [13] Liu, X., Jawahar, H. K., Azarpeyvand, M., and Theunissen, R., "Aerodynamic performance and wake development of airfoils with serrated trailing-edges," *AIAA Journal*, Vol. 55, No. 11, 2017, pp. 3669–3680. <https://doi.org/10.2514/1.J055817>.
- [14] Mayer, Y. D., Lyu, B., Jawahar, H. K., and Azarpeyvand, M., "A semi-analytical noise prediction model for airfoils with serrated trailing edges," *Renewable Energy*, Vol. 143, 2019, pp. 679–691. <https://doi.org/10.1016/j.renene.2019.04.132>.
- [15] Herr, M., and Dobrzynski, W., "Experimental investigations in low-noise trailing-edge design," *AIAA Journal*, Vol. 43, No. 6, 2005, pp. 1167–1175. <https://doi.org/10.2514/1.11101>.
- [16] Geyer, T., Sarradj, E., and Fritzsche, C., "Measurement of the noise generation at the trailing edge of porous airfoils," *Experiments in Fluids*, Vol. 48, No. 2, 2010, pp. 291–308. <https://doi.org/10.1007/s00348-009-0739-x>.
- [17] Ali, S. A. S., Azarpeyvand, M., and Da Silva, C. R. I., "Trailing-edge flow and noise control using porous treatments," *Journal of Fluid Mechanics*, Vol. 850, 2018, pp. 83–119. <https://doi.org/10.1017/jfm.2018.430>.
- [18] Showkat Ali, S. A., Azarpeyvand, M., Szőke, M., and Ilário Da Silva, C. R., "Boundary layer flow interaction with a permeable wall," *Physics of Fluids*, Vol. 30, No. 8, 085111, 2018. <https://doi.org/10.1063/1.5043276>.

- [19] Clark, I. A., Devenport, W., Jaworski, J. W., Daly, C., Peake, N., and Glegg, S., “The noise generating and suppressing characteristics of bio-inspired rough surfaces,” *20th AIAA/CEAS Aeroacoustics Conference*, Delft, The Netherlands, 2014, p. 2911. <https://doi.org/10.2514/6.2014-2911>.
- [20] Clark, I. A., Alexander, W. N., Devenport, W., Glegg, S., Jaworski, J. W., Daly, C., and Peake, N., “Bioinspired trailing-edge noise control,” *AIAA Journal*, Vol. 55, No. 3, 2017, pp. 740–754. <https://doi.org/10.2514/1.J055243>.
- [21] Afshari, A., Azarpeyvand, M., Dehghan, A. A., Szöke, M., and Maryami, R., “Trailing-edge flow manipulation using streamwise finlets,” *Journal of Fluid Mechanics*, Vol. 870, 2019, pp. 617–650. <https://doi.org/10.1017/jfm.2019.249>.
- [22] Afshari, A., Dehghan, A. A., and Azarpeyvand, M., “Novel three-dimensional surface treatments for trailing-edge noise reduction,” *AIAA Journal*, Vol. 57, No. 10, 2019, pp. 4527–4535. <https://doi.org/10.2514/1.J058586>.
- [23] Bodling, A., and Sharma, A., “Numerical investigation of noise reduction mechanisms in a bio-inspired airfoil,” *Journal of Sound and Vibration*, Vol. 453, 2019, pp. 314–327. <https://doi.org/10.1016/j.jsv.2019.02.004>.
- [24] Gstrein, F., Zang, B., and Azarpeyvand, M., “Application of Finlets for Trailing Edge Noise Reduction of a NACA 0012 Airfoil,” *AIAA Aviation Forum*, Virtual Event, 2020, p. 2502. <https://doi.org/10.2514/6.2020-2502>.
- [25] Mayer, Y. D., Jawahar, H. K., Szöke, M., Ali, S. A. S., and Azarpeyvand, M., “Design and performance of an aeroacoustic wind tunnel facility at the University of Bristol,” *Applied Acoustics*, Vol. 155, 2019, pp. 358–370. <https://doi.org/10.1016/j.apacoust.2019.06.005>.
- [26] Sarradj, E., and Herold, G., “A Python framework for microphone array data processing,” *Applied Acoustics*, Vol. 116, 2017, pp. 50–58. <https://doi.org/10.1016/j.apacoust.2016.09.015>.
- [27] Celik, A., Bowen, J. L., and Azarpeyvand, M., “Effect of trailing-edge bevel on the aeroacoustics of a flat-plate,” *Physics of Fluids*, Vol. 32, No. 10, 2020, p. 105116. <https://doi.org/10.1063/5.0024248>.
- [28] Yardibi, T., Bahr, C., Zawodny, N., Liu, F., Cattafesta III, L. N., and Li, J., “Uncertainty analysis of the standard delay-and-sum beamformer and array calibration,” *Journal of Sound and Vibration*, Vol. 329, No. 13, 2010, pp. 2654–2682. <https://doi.org/10.1016/j.jsv.2010.01.014>.
- [29] Mayer, Y. D., “Aeroacoustic Characteristics of Static and Dynamic Stall,” Ph.D. thesis, University of Bristol, 2020.
- [30] Gravante, S. P., Naguib, A. M., Wark, C. E., and Nagib, H. M., “Characterization of the pressure fluctuations under a fully developed turbulent boundary layer,” *AIAA Journal*, Vol. 36, No. 10, 1998, pp. 1808–1816. <https://doi.org/10.2514/2.296>.
- [31] Vemuri, S. H. S., Liu, X., Zang, B., and Azarpeyvand, M., “On the use of leading-edge serrations for noise control in a tandem airfoil configuration,” *Physics of Fluids*, Vol. 32, No. 7, 2020. <https://doi.org/10.1063/5.0012958>.
- [32] Mayer, Y. D., Zang, B., and Azarpeyvand, M., “Aeroacoustic characteristics of a NACA 0012 airfoil for attached and stalled flow conditions,” *25th AIAA/CEAS Aeroacoustics Conference*, Delft, The Netherlands, 2019, p. 2530. <https://doi.org/10.2514/6.2019-2530>.

- [33] Zang, B., Mayer, Y. D., and Azarpeyvand, M., “An experimental investigation on the mechanism of tollmien-schlichting waves for a naca 0012 aerofoil,” *25th AIAA/CEAS Aeroacoustics Conference*, Delft, The Netherlands, 2019, p. 2609. <https://doi.org/10.2514/6.2019-2609>.
- [34] Bendat, J. S., and Piersol, A. G., *Random data: Analysis and measurement procedures*, 4th ed., John Wiley & Sons, Inc., 2010.
- [35] Garcia-Sagrado, A., and Hynes, T., “Wall pressure sources near an airfoil trailing edge under turbulent boundary layers,” *Journal of Fluids and Structures*, Vol. 30, 2012, pp. 3–34. <https://doi.org/10.1016/j.jfluidstructs.2011.12.007>.
- [36] Kline, S. J., and McClintock, F. A., “Describing Uncertainties in Single-Sample Experiments,” *ASME Mechanical Engineering*, Vol. 75, 1953, pp. 3–8.
- [37] Brooks, T. F., Marcolini, M. A., and Pope, D. S., “Airfoil trailing-edge flow measurements,” *AIAA Journal*, Vol. 24, No. 8, 1986, pp. 1245–1251. <https://doi.org/10.2514/3.9426>.
- [38] Garcia Sagrado, A. P., “Boundary layer and trailing edge noise sources,” Ph.D. thesis, University of Cambridge, 2008.
- [39] Hutcheson, F. V., and Brooks, T. F., “Effects of angle of attack and velocity on trailing edge noise determined using microphone array measurements,” *International Journal of Aeroacoustics*, Vol. 5, No. 1, 2006, pp. 39–66. <https://doi.org/10.1260/147547206775220425>.
- [40] Schlichting, H., and Kestin, J., *Boundary-layer theory*, 7th ed., McGraw-Hill, New York, USA, 1979.
- [41] Spalding, D. B., “A single formula for the law of the wall,” *Journal of Applied Mechanics, Transactions ASME*, Vol. 28, No. 3, 1960, pp. 455–458. <https://doi.org/10.1115/1.3641728>.
- [42] Farabee, T. M., and Casarella, M. J., “Effects of surface irregularity on turbulent boundary layer wall pressure fluctuations,” *Journal of Vibration and Acoustics, Transactions of the ASME*, Vol. 106, No. 3, 1984, pp. 343–350. <https://doi.org/10.1115/1.3269200>.
- [43] Leclercq, D. J. J., Jacob, M. C., Louisot, A., and Talotte, C., “Forward-backward facing step pair: Aerodynamic flow, wall pressure and acoustic characterisation,” *7th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Maastricht, The Netherlands, 2001, p. 2249. <https://doi.org/10.2514/6.2001-2249>.
- [44] Takahashi, H., Iijima, H., Kurita, M., and Koga, S., “Evaluation of skin friction drag reduction in the turbulent boundary layer using riblets,” *Applied Sciences (Switzerland)*, Vol. 9, No. 23, 5199, 2019. <https://doi.org/10.3390/app9235199>.