Pressure shielding mechanism of canopies for trailing edge noise reduction in aerofoils

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Abstract

The pressure shielding mechanism of bio-inspired surface treatment, called canopies, has been investigated experimentally and applied to reduce trailing edge noise generated by aerofoils. Surface pressure experiments on the aerofoil section show that canopies can attenuate surface pressure in two frequency ranges, Δf_1 = 0.3 to 1.5 kHz and Δf_2 = 2.3 to 12 kHz, at some critical canopies' height from the aerofoil trailing edge. Canopies with an Open-Area-Ratio (OAR) of 50 % placed closer (h/δ=0.08) to the aerofoil trailing edge surface tend to increase attenuation with frequency, without any low-frequency peak attenuation. This high-frequency attenuation can be due to the mechanism of turbulence energy dissipation via surface friction from the canopies. As h/δ increases, the low-frequency attenuation in the surface pressure increases, with a peak value of 5 dB for a critical height of h/δ = 0.12. For $h/\delta \geq$ 0.16, both the low- and high-frequency attenuation reduces and becomes almost zero for h/δ = 0.5. Furthermore, the mechanism of pressure shielding provided by the canopy treatment is shown to be a local phenomenon, for 60% <OAR < 90 % and very sensitive to the location of the canopy itself. The maximum attenuation in surface pressure is seen for the canopy geometries with small rod diameters and spacing. The optimum canopy geometry, based on surface pressure measurements, was applied near the trailing edge of the NACA0012 aerofoil. This study demonstrates, for the first time, that canopies can reduce broadband noise levels by 15 dB in the frequency range between 2.3 and 12 kHz at the far-field if they are appropriately scaled to the turbulent boundary-layer flow at the aerofoil surface. The work presented in this abstract will be extended in the full-length paper, including a more detailed parametric study.

I. Introduction

Trailing edge noise is one of the most dominant sources of noise at higher frequencies produced by surfaces interacting with airflow, like wind-turbines and turbofans. It is well known that the aerofoil trailing edge noise is generated when the pressure fluctuations, caused by the boundary layer turbulence in the vicinity of the aerofoil surface, convect

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downstream past the trailing edge. Consequently, more effective designs of surface treatments are required to attain the desired levels of noise reduction, particularly as future requirements for air moving/lifting equipment are growing rapidly.

Several approaches have been proposed in the literature to reduce the trailing edge noise like serrations, porous surface treatments, flexible trailing edges, and boundary layer flow control[1–5]. However, in recent years much research has been devoted to the design of bio-inspired surface treatments such as Finlets fences and rails to realise a significant reduction of trailing edge noise. Such unconventional surface treatment concepts have been studied to achieve broadband noise reduction, predominantly in the frequency range of 2 - 5 kHz, while maintaining aerodynamic performances in par with the baseline. For example, Gstrein et al. [6] investigated the noise reduction performance of Finlet fences by shifting their position upstream towards the leading edge. This experimental work was an extension of the near-field study carried out by Afshari et al. [7] and [8] on a flat plate. Bodling and Sharma [9] numerically investigated the Finlet fences proposed by Clark et al. [10] on NACA0012 aerofoil. The authors observed that the normalized turbulence kinetic energy is redistributed from the trailing edge surfaces of the aerofoils to the Finlet fences. The above experimental and numerical study on the aerofoil trailing edge noise reduction mainly focused on the application of Finlet fences design, except for the work by Clark et al. [10] which considered the potential of a canopy-like (Finlet rails) surface treatment to reduce the trailing edge noise generated by flow over an aerofoil. It was shown that, compared with the untreated aerofoil, the treated aerofoils (Finlet fences) were effective in providing a broadband reduction of trailing-edge noise of up to 10 dB between 2 and 5 kHz. It was also shown that the surface treatments were effective over a range of angle-of-attack that extends to over 9 deg from zero-lift. In addition, aerofoil treatments did not adversely affect the aerodynamic performances. Also, the experimental work of Clark et al. [10] included a brief study on the Finlet rail, a series of rods supported from the aerofoil trailing edge surface. This work focused on the effect of Finlet rail extension, height, and doubling of the diameter and spacing on the radiated trailing edge noise spectra. Clark et al. [10] showed that increasing the height of the Finlet rails from the aerofoil trailing edge surface deteriorates the noise reduction benefits. This observation was associated with the prevention of the smaller-scale turbulent fluctuations from being de-correlated along the aerofoil span. Additionally, the work of Clark et al. [10] showed a decrease in the noise reduction due to the increase in rails (canopies) height. These findings from previous studies, directly conducted on the aerofoil, where the fences or canopies like surface treatments were hypothesised to be lifting low-frequency flow structures from the trailing edge, are inconclusive.

Hari et al. [11] recently performed a detailed experimental study in a turbulent wall-jet facility to quantify and understand the attenuation in the surface pressure beneath the canopies. The results showed that the attenuation at low frequencies scaled with the canopy height and stream-wise flow velocity at the canopy height. At the high frequency, the attenuation was shown to scale with the kinematic viscosity of air and square of stream-wise flow velocity at the canopy height. However, it was not shown if the reduction scaling laws proposed in the literature were a non-local phenomenon or restricted locally beneath the canopies/close to the fences.

As a result, the experimental work described in this paper follows up on the study of Prof. Devenport, Clark et al. [10], Hari et al. [11] and other researchers from Virginia Tech. The objectives of the paper are:

1) to assess the aeroacoustic performance of Canopies applied to NACA0012 aerofoil.
2) to establish the fundamental mechanisms by which Canopies reduce aerofoil trailing edge noise.
3) to understand whether surface pressure scaling laws proposed in the literature is a non-local phenomenon or restricted locally beneath the canopies.

Additionally, this study will be useful for exploring and optimising other novel surface treatments that can reduce aerofoil self-noise.

II. Experimental set-up

The aerofoil noise measurements were carried out at the ISVR's open-jet wind tunnel facility. The wind tunnel nozzle is mounted inside an anechoic chamber of dimensions 8 m x 8 m x 8 m, and the size of the nozzle exit is 150 mm x 450 mm with a contraction ratio of 25:1. It provides a quiet and low-turbulence flow (<0.4 %) for aerofoil noise measurements. The maximum flow speed at the exit of the nozzle is 100 m/s. However, the aerofoil noise measurements were made at speeds 20, 30, 40, and 60 m/s. As shown in **Fig. 1**, far-field noise measurements were made using 15 half-inch condenser microphones (B&K type 4189) located in the mid-span plane of the aerofoil and at a constant radial distance of 1.2 m from the aerofoil mid-chord position. In this study, the 0.2 m chord NACA0012 aerofoil was used for the experiments. As shown in Fig. 2a, the experimental test section consists of NACA0012 aerofoil supported by side plates. The side plates were flush mounted at the nozzle exit section and maintains the flow two-dimensionality. The aerofoil noise was measured at 0, 5^o and 10^o angle of attack (α). The aerofoils with surface treatments were 3-D

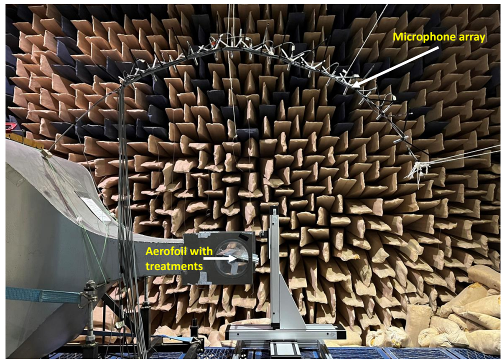
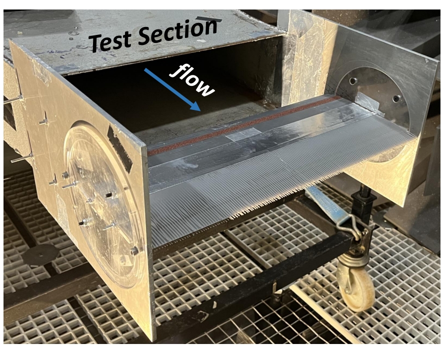
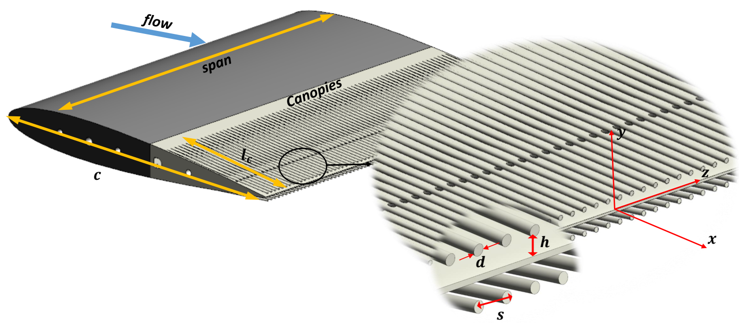


Fig. 1 Test set-up for aerofoil noise measurement. Shown in the picture are the open-jet wind tunnel nozzle, NACA0012 aerofoil and microphone polar array.

printed in two parts for the ease of manufacturing and testing using a Stereolithography (SLA) printer. **Fig. 2b** shows the second part of the aerofoil, of length 90 mm, with surface treatments starting from x/c =0.575. The incoming flow was tripped on both suction and pressure sides to prevent tonal noise generation due to Tollmien-Schlichting waves convecting in the laminar boundary layer the flow. For tripping the flow, a rough band of tape of width 2.5 cm was applied at 10% of chord from the leading edge. The tape has roughness of SS 100, corresponding to a surface roughness of 140 μm.



(a) Wind-tunnel test section.



(b) CAD geometry of the NACA0012 aerofoil with surface treatments.

Fig. 2 Geometry of the NACA0012 aerofoil section treated with canopies.

For the far-field noise measurements, the microphones are placed at radiation angles(θ) of between 30^o and 120^o measured relative to the aerofoil mid-chord position. The noise measurements were made for a time duration of 10 sec at a sampling frequency of 40 kHz. In the post processing, the noise spectra was calculated with a window size of 512 data points corresponding to a frequency resolution of 78.125 Hz.

Fig. 2b shows the schematic of the NACA0012 trailing edge treated with canopies. In this experimental study, the height (h), spacing (s), and length (l) for the canopy, as shown in Fig. 2b (d), is set to 2 mm, 1.5 mm, and 65 mm, respectively. The geometrical parameters h, s, and l are investigated in detail, and the results will be presented in the full-length paper. The surface treatments were applied on both sides of the aerofoil.

The sound power level per unit span PWL was calculated from the measured pressure signal between radiation angles of 30^o and 120^o to assess the efficiency of noise reduction obtained with the surface treatments. The reduction in sound power level per unit frequency due to the introduction of the surface treatments is calculated from the PWL(f) and is given by,

$$\Delta PWL\,(f) = 10log10\left(\frac{\sum_i S_{pp}\,(f,\theta_i)_b}{\sum_i S_{pp}\,(f,\theta_i)_t}\right) \tag{1}$$

where $S_{pp}(f,\theta_i)_b$ & $S_{pp}(f,\theta_i)_t$ is the pressure spectral density measured at i^{th} microphone for untreated and treated cases, respectively.

III. Preliminary results and discussion

A. Far-Field noise data

In this section, the noise reduction spectra (ΔSPL) are presented at 0^o angle of attack, and for the velocities U_o = 20, 30, and 40 m/s, for the canopies - supported by one rod. The geometry of the surface treatment is derived from the concepts previously presented by Clark et al. [10]. Measurements were also made at a higher geometrical angle of attack (5^o and 10^o) and other jet velocities, but the results are not presented here as the observations do not vary significantly.

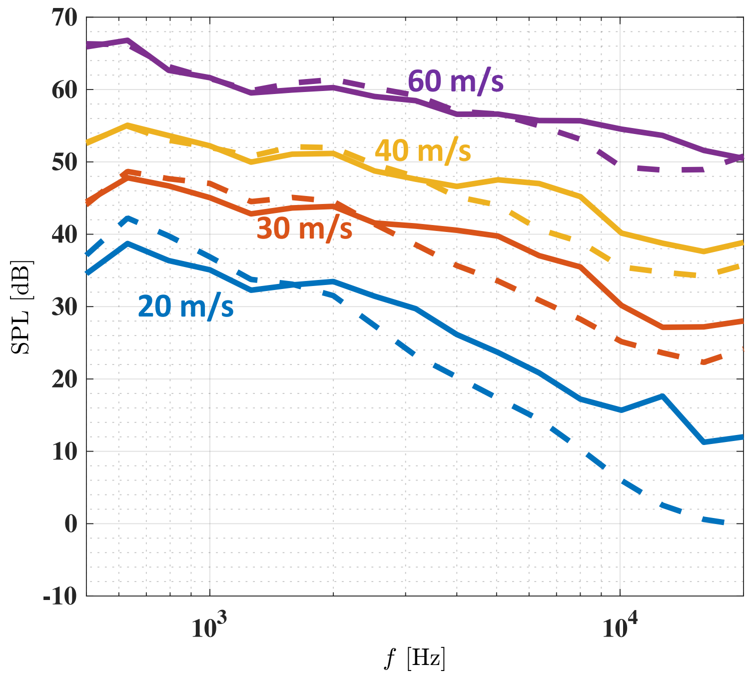


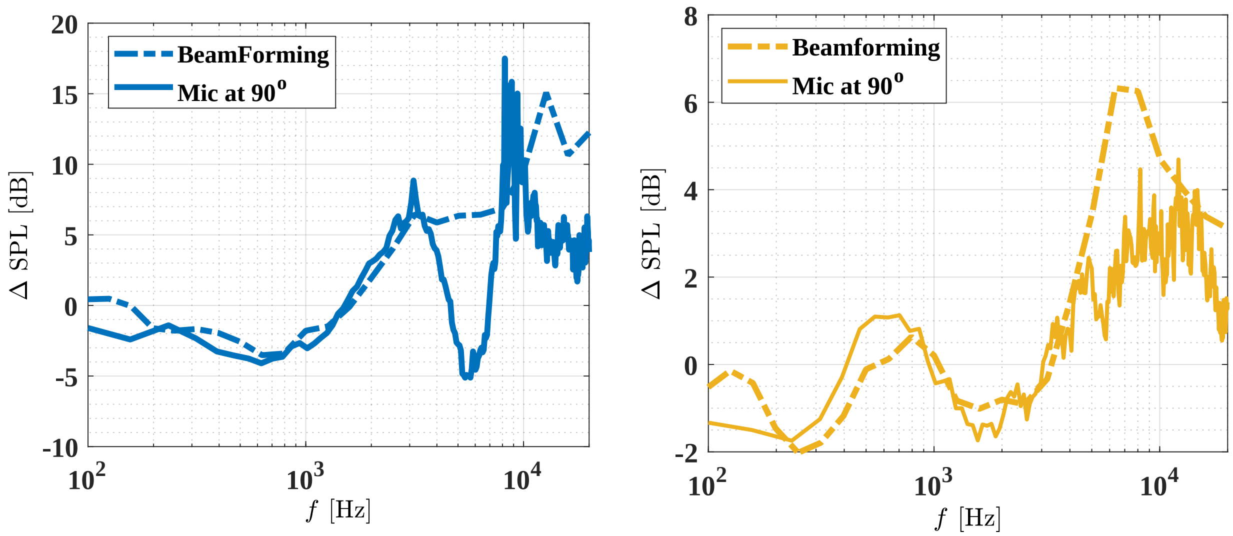
Fig. 3 Sound pressure level spectra comparisons between baseline (solid lines) and surface treated aerofoil (dashed line). The flow velocity is between 20 and 60 m/s. The angle of attack is 0.

Fig. 3 shows the noise spectra measured using an acoustic beam-forming array of 40 microphones. The details about the beam-forming array will be included in the full-length article. In Fig. 3, the solid line represents the baseline case, the untreated aerofoil, and the dashed line represents the aerofoil treated with canopies of d = 1 mm and s = 2 mm (OAR = 50 %). The comparison between the untreated and treated aerofoil noise spectra shows that the canopies can reduce broadband sound pressure level by up to 14 dB for the normalised height h/δ = 0.12 and at the mean-flow speed of 20 m/s. Furthermore, the noise reduction increases with the frequency. It can also be noted that the level of noise reduction decreases with the increasing flow velocity, and the peak noise reduction value decreases. Therefore, it appears that the maximum noise reduction only occurs when the dimensions of the canopies are at least a certain fraction of the boundary layer thickness(δ). This will be shown later in the surface pressure measurements

In addition to the beam-forming array, free-field microphones were placed 90^o from the mid-span of an aerofoil, respectively, to measure noise reduction. The results are shown in **Fig.4** . Note that the sound pressure level in the ΔSPL spectra associated with the background noise levels generated by the facility is filtered out for the free-field microphone. This is because as the jet velocity increases, background noise contribution increases at higher frequencies compared to the lower frequencies, which is one of the main reasons for using the beam-forming array.

As mentioned earlier, from Fig. 4a, the aerofoil treated with canopies provides a noise level reduction of at least 3 dB for frequencies between 2 and 12 kHz, with a peak reduction of around 14 dB at 12 kHz (see the beam-forming spectra) at a flow velocity of 20 m/s. Interestingly, the free-field microphone data shows a dip in the noise reduction spectra between 5 and 6 kHz. Apart from the frequency range between 5 and 6 kHz, the noise reduction observed from the beam-forming array agrees well with the free-field microphone measurements. The noise reduction spectra obtained from the beam-forming array clearly show that the aerofoil trailing edge treated with canopies at the height of h/δ = 0.12 tend to provide attenuation only at high-frequency range (Δf_2 = 2.3 - 12 kHz). This high-frequency attenuation can be due to the mechanism of turbulence energy dissipation via surface friction from the canopies.

At 40 m/s, as shown in Fig. 4b, the overall noise reduction provided by canopies of d = 1 mm, s = 1 mm, and for a fixed height remains significant with a peak reduction of 6 dB. However, compared to noise reductions seen at 20 m/s, there is a considerable drop in the peak value (from 14 dB to 6 dB). This indicates that the non-dimensional height h/δ increases with increasing flow speed which reduces both the low- and high-frequency attenuation provided by the canopies.



(a) Far-field noise reductions at 20 m/s.

(b) Far-field noise reductions at 40 m/s.

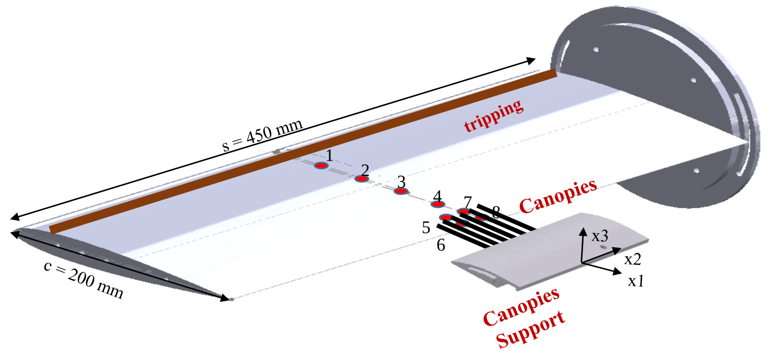
Fig. 4 Noise reduction comparisons between measurements from Far-field microphone located at 90^o above aerofoil midspan and beam-forming. Mean-flow velocity ranges between 20 and 60 m/s. The angle of attack is 0.

B. surface pressure measurements

The unsteady surface pressure was measured using the miniature microphones, Knowles FG-23329-P07 type, at the mid-span at x/c = 0.98. The surface pressure sensors are remotely connected to the aerofoil surface and the location of the pressure tapping are shown in **Fig. 5**. The pressure sensors' locations are chosen to cover the x/c in the range of 0.63 to 0.98. In addition, the surface pressure data without canopies was recorded for the baseline. This has been done to avoid the influence of the support structure on the surface pressure measurements. **Fig. 5** shows the test setup for the surface pressure measurements. Canopies of diameter ranging between 0.5 mm and 2.5 mm, with OAR 20 to 90 %, were tested for heights, h, ranging between 1 mm to 12 mm. The mean-flow velocities were 20, 30, and 40 m/s. The full-length paper will detail the test setup and surface pressure measurements.

Fig. 6a compares a representative case of wall pressure spectra for a canopy of rod diameter (d) 0.8 mm with spacing (s) 1.5 mm (OAR = 0.5, approximately) for increasing height, h (h/δ = 0.0.8 to 0.5). The flow velocity is 20 m/s. Canopies placed at h/δ=0.08 to the aerofoil trailing edge surface tend to increase attenuation with frequency without any low-frequency peak attenuation. This high-frequency attenuation can be due to the mechanism of turbulence energy dissipation via surface friction from the canopies. As h/δ increases, the low-frequency attenuation in the surface pressure increases, with a peak value of 5 dB for a critical height of h/δ = 0.12. For $h/\delta \geq 0.16$, both the low- and high-frequency attenuation reduces and becomes almost zero for h/δ = 0.5.

Mics	x/c
1	0.33
2	0.5
3	0.63
4	0.80
5	0.92
6	0.98
7	0.92
8	0.98



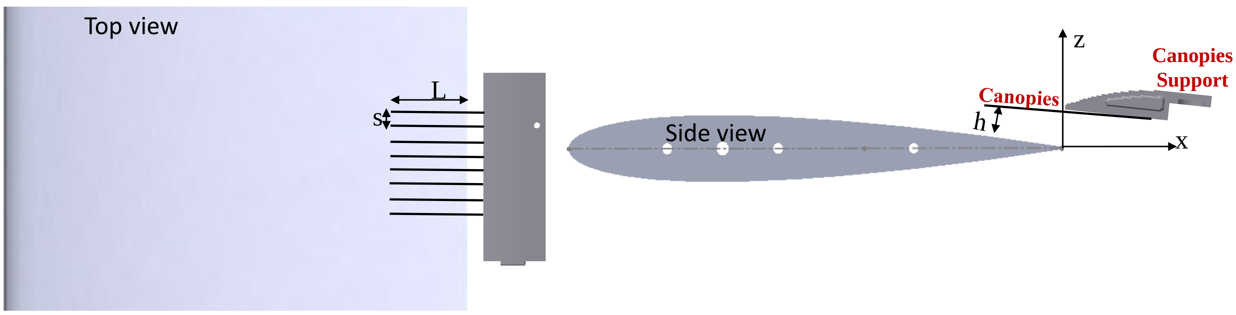
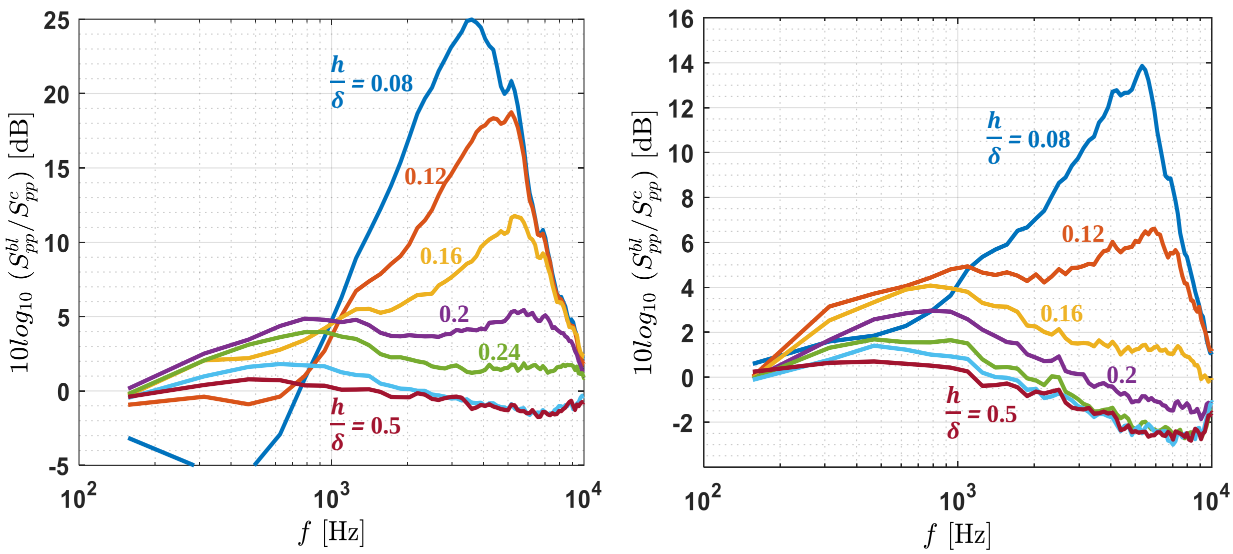


Fig. 5 Schematic of the surface pressure measurement test set-up.



(a) d = 0.8 mm, s =1.5 mm

(b) d = 1.5 mm, s = 3 mm.

Fig. 6 Surface pressure attenuation spectra for Canopies with diameter 0.8 and 1.5 mm at different heights. Mean-flow velocity is 20 m/s.

Fig. 6b shows the surface pressure attenuation spectra of the canopy with d = 1.5 mm and s = 3 mm. Similar to canopies of d = 0.8 mm, we observe a similar trend in surface pressure reductions for canopies of d = 1.5 mm placed at h/δ=0.08, which tend to increase attenuation with frequency. For $h/\delta \geq 0.16$, both the low- and high-frequency attenuation reduces and becomes almost zero for $h/\delta = 0.5$. There is a shift in the frequency of the peak reduction with increasing canopy diameter. In addition, there is also a notable reduction of the amplitude of the peak reduction with

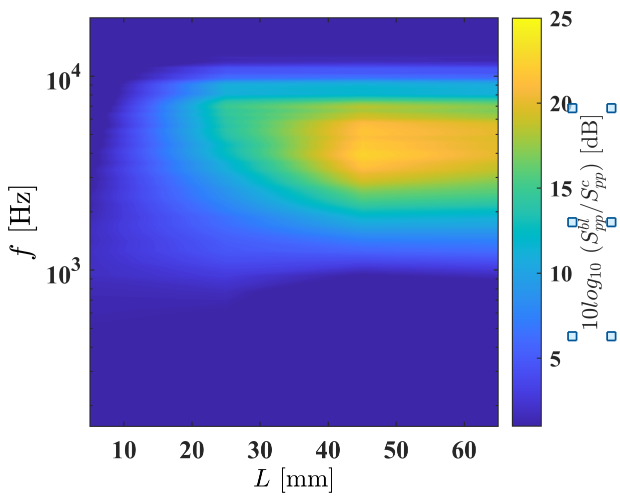


Fig. 7 Surface pressure attenuation spectra for canopies with d = 0.8 mm, s =1.5 mm, and h/δ =0.08 for varying length. Mean-flow velocity is 20 m/s.

increasing rod diameter (25 dB-> 14dB).Furthermore, the mechanism of pressure shielding provided by the canopy treatment is shown to be a local phenomenon, for 60% <OAR < 90 % and very sensitive to the location of the canopy itself. The maximum attenuation in surface pressure is seen for the canopy geometries with small rod diameters and spacing, verified for canopies of rod diameter d = 0.5 mm. The results are not shown here for brevity and will be presented in the full-length paper.

IV. Summary and Future plan

The preliminary experimental work on applying surface treatments on the NACA0012 aerofoil leads to the following observations.

1) The far-field noise results show that the canopies can provide significant noise level reductions in different frequency ranges depending on their geometry relative to the boundary layer thickness.
2) The surface pressure measurements indicated that the canopies placed at h/δ=0.08 to the aerofoil trailing edge surface tend to increase attenuation with frequency without any low-frequency peak attenuation. This high-frequency attenuation can be due to the mechanism of turbulence energy dissipation via surface friction from the canopies. As h/δ increases, the low-frequency attenuation in the surface pressure increases, with a peak value of 5 dB for a critical height of h/δ = 0.12. For $h/\delta \geq 0.16$, both the low- and high-frequency attenuation reduces and becomes almost zero for h/δ = 0.5.

In the final draft of the paper the following results and sections will be included:

A. Far-Field and surface pressure measurements

A detailed experimental study will be carried out

1) to understand whether surface pressure scaling laws proposed in the literature are non-local or restricted locally beneath the canopies/close to the fences.

2) to conduct a detailed near-field measurement with varying canopy design parameters to understand the mechanism behind the surface pressure reduction in the presence of canopies.
3) to investigate the application of the TNO/Blake model for predicting the surface pressure in the vicinity of surface treatments, taking into account the periodic behaviour of the flow across the span with treatment spacing.

Additionally, this study will help to explore and optimise other novel surface treatments that can reduce aerofoil noise.

B. Hot-wire measurements

The final draft of the paper will include a detailed analysis of the hot-wire measurements of the flow field behind the trailing edge of the aerofoil treated with canopies.

C. Discussion of results and conclusion

A detailed analysis on the measurement results and a conclusion section.

Acknowledgments

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