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# REDUCTION OF TURBULENCE-AEROFOIL INTERACTION NOISE BY THE USE OF KEVLAR-COVERED AIR GAPS

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This work is a fundamental experimental investigation on reducing the noise caused by the interaction of a turbulent stream with an aerofoil by using a Kevlar section downstream of the aerofoil leading edge. It has been shown previously by the authors that the noise radiated by two flat plates in a tandem configuration in a turbulent flow is significantly reduced at low frequencies relative to a baseline aerofoil. One of the mechanisms of such noise reductions is attributed to an effective shortening of the chord which leads to generally weaker radiation. Additional noise is however generated at higher frequencies caused by the interaction of the wake shed from the upstream plate impinging onto the leading edge of the downstream plate. The current work proposes to bridge the air gap between the two flat-plate aerofoil sections with Kevlar fabric. It is shown that this technology is capable of suppressing the additional noise penalty while still providing significant levels of noise reduction both in flat plates and thin aerofoil geometries representative of outlet guide vanes in aero-engine applications.

Keywords: Turbulence-aerofoil interaction noise, tandem configurations.

## 1. Introduction

The interaction of a turbulent flow with an aerofoil is one of the main generation mechanisms of broadband noise in many applications. These range from home appliances to industrial heating and ventilation systems, wind turbines and turbofan aircraft engines. In the latter, turbulent flow in the wake of the fan impinges onto the downstream stator blades (Outlet Guide Vanes (OGV)) and generates noise.

Different technologies have been investigated in the literature to reduce this noise source, such as serrations [1, 2, 3, 4] and porosity [5, 1, 6, 7] introduced onto the aerofoil leading edge. These have been shown to be very effective in reducing noise but often present the disadvantage of producing an aerodynamic performance penalty [8] since most of the lift is generated in the leading edge region. It was recently shown in [9] however that installing a porous section downstream of the leading edge can still yield significant noise reductions while reducing adverse effects on aerodynamic performance [10].

The reduction of turbulence interaction noise by using porosity located downstream of an aerofoil leading edge has been recently studied experimentally by the authors in [11]. A principal finding of the paper was that the noise reduction spectra at low frequencies for a flat plate with downstream porosity are almost identical in shape to that of two flat plates in a tandem configuration, in which the porous section is effectively replaced by an air gap (100% porosity). Multiple noise reduction mechanisms were hypothesised, including (1) edge-to-edge interactions due to secondary vorticity driven by the initial vortex and (2) a modified leading edge radiation due to a shorter effective chord. However, additional noise was observed at higher frequencies. This was especially severe in the tandem configuration, which showed strong interaction noise radiated due to the impingement of the wake shed from the upstream plate onto the leading edge of the downstream plate.

The gap between the two flat plates in a tandem configuration is bridged with a Kevlar fabric in the current experimental study. A Kevlar layer is also applied on a thin NACA4505 aerofoil with downstream porosity. The aim of this study is to investigate the potential of this technology to suppress the unwanted interaction and self-noise sources in tandem plates and aerofoils with downstream porosity.

## 2. Description of the experiment

### 2.1 ISVR open-jet facility

The experiments in this investigation were carried out at the Institute of Sound and Vibration Research's open-jet wind tunnel facility. The wind tunnel is located within the newly refurbished anechoic chamber, of dimension 6.7 m x 6.7 m x 4.9 m. The walls are acoustically treated with open-cell polyurethane wedges whose cut-off frequency is 70 Hz. The nozzle has dimensions of 150 mm x 450 mm and a contraction ratio of 25:1 which provides a maximum flow speed of 100 m/s.

The inflow turbulence was generated by using a bi-planar rectangular grid of 460 x 600 $\text{mm}^2$ made of wooden bars of 12 mm width separated by 34 mm. The grid was located in the contraction section 63 cm upstream of the nozzle exit. The velocity spectra measured at 145 mm from the nozzle exit has 2.5% turbulence intensity and a 7.5 mm streamwise integral length-scale [3].

Far-field noise measurements were made using 10 quarter inch GRAS 40PL-10 CCP microphones located at a constant radial distance of 1.2 m from the mid span of the flat plate leading edge. These microphones are placed at emission angles of between $50^\circ$ and $120^\circ$ measured relative to the downstream jet axis. Measurements were carried out for 10 s at a sampling frequency of 40 kHz, and the noise spectra were calculated with a window size of 2048 data points corresponding to a frequency resolution of 19.53 Hz and a Bandwidth-Time (BT) product of about 200. Noise reductions are presented in terms of the Sound Pressure Level SPL$(f)$ at individual microphone locations and the Sound Power Level spectra PWL$(f)$ calculated by integrating the pressure spectra over the microphone array.

### 2.2 Flat plate configurations

The experimental set-up consisted of two rigid flat plates arranged in tandem configuration and separated by an air gap or slot. This slot was covered with Kevlar fabric taped at the trailing edge of the first plate and at the leading edge of the second plate. The characteristics of the Kevlar fabric are specified in Table 1. A schematic diagram of the tandem plates and related nomenclature is shown in Fig. 1. Side plates were mounted to the nozzle exit to support the flat plates and maintain a two-dimensional flow around them. The side plates used in this instance contained streamwise slots to allow for changing the distance $l$ between the two plates, that is the horizontal distance between the trailing edge of the first plate (TE1) and the leading edge of the second plate (LE2), and to tension the Kevlar fabric. The leading edge of the first flat plate was located at 150 mm ($\approx$ one chord) downstream of the nozzle exit.

Table 1: Characteristics of the tested Kevlar fabric

| Fabric ID | Weave | Weight($g/m^2$) | Material | Yarn Tex (Warp/Weft) | Setting th/cm (Warp/Weft) | Thickness (mm) |
|---|---|---|---|---|---|---|
| K0120 | Plain | 61 | Kevlar 49 | 22/22 | 13.5/13.5 | 0.12 |

Results were obtained for different chords of the first plate $c_1$ and distances between the plates $l$ of 20, 30 and 50 mm for flow speeds $U$ of 20 and 40 m/s. All cases were performed both for an air gap between the plates and a Kevlar cloth bridging the two flat plates.

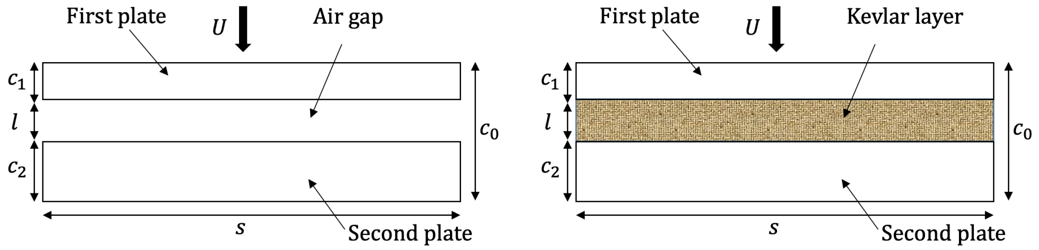


Figure 1: Schematic diagram of two flat plates in tandem configuration with an air gap (left) and a Kevlar fabric (right).

### 2.3 Kevlar-covered aerofoils with downstream porosity

In addition to the flat plate study, the use of Kevlar was also investigated to enhance the performance of aerofoils with downstream porosity. The treatment was installed over the porous section of a NACA4505 aerofoil of $c_0$=150 mm chord previously investigated by the authors [11]. The aerofoil was 3-D printed with rows of vertically orientated circular holes with a hole diameter of $D$=3 mm and spacing of $T/D = 1.67$, where $T$ is the distance between the centers of two neighbouring holes. The porous section was located $l_0/c_0 = 0.13$ downstream of the leading edge and extended over $l/c_0 = 0.33$. The Kevlar fabric was bonded on top of the porous section as sketched in Fig. 2

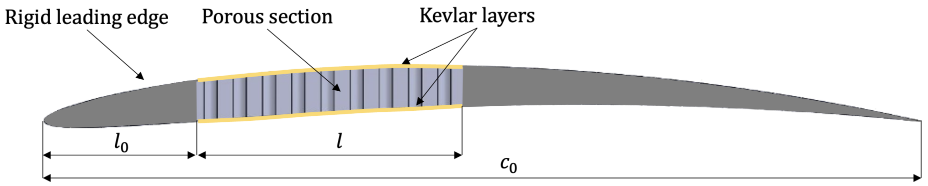


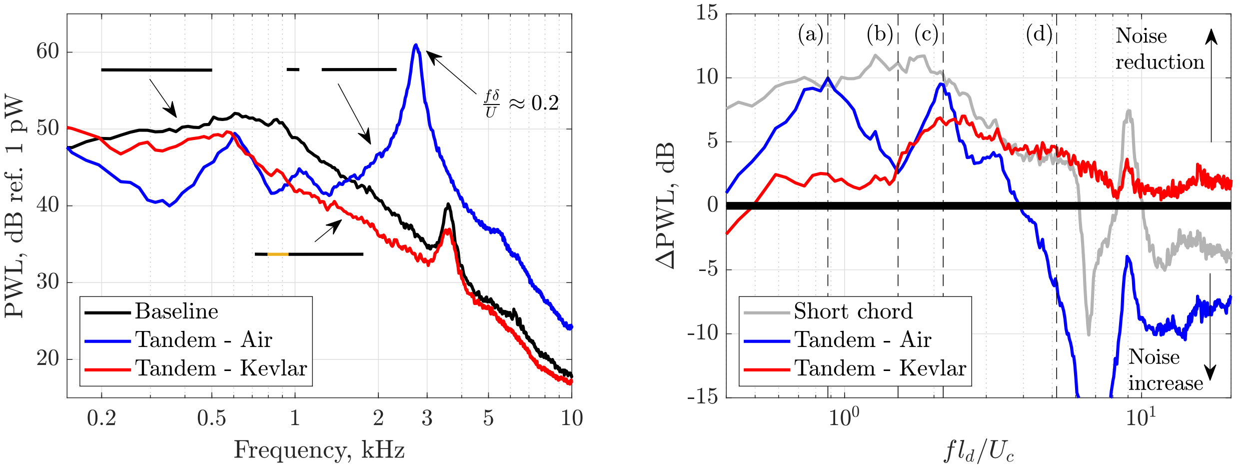
Figure 2: Schematic diagram of the NACA4505 aerofoil with downstream porosity and Kevlar fabric.

## 3. Acoustic performance of tandem flat plates and Kevlar-covered air gaps

We first start by comparing the sound power spectra measured for a baseline flat plate aerofoil and two flat plates in a tandem configuration. These are shown in Fig. 3a for $c_1/c_0 = 0.12$, $l/c_0 = 0.30$ and $U = 40$ m/s, in which both the results for an air gap and Kevlar fabric are presented. The tandem configuration with an air gap (blue curve) is very effective in reducing noise at low frequencies, with up to 10 dB of noise reduction at f=350 Hz. However, it results in an increase of noise at frequencies above 1.5 kHz, which peaks at the vortex shedding frequency of $f\delta/U \approx 0.2$, where $\delta$ is the effective thickness of the flat plate. This is most likely caused by the interaction of the wake shed from the upstream plate with the leading edge of the downstream plate. One of the main findings of this paper is that by bridging the air gap between the two plates with a Kevlar fabric (red curve) any additional noise source is completely suppressed as observed in Fig. 3a. The tandem configuration with the Kevlar fabric is found to yield noise reductions over practically all frequencies with up to 7 dB of noise reduction at around 1 kHz. We note that similar results are also obtained at other inflow velocities $U$.

The same experimental data of Fig. 3a is presented in the form of noise reduction spectra in Fig. 3b. Also shown is the noise reduction spectra obtained by just considering the upstream plate of chord $c_1$, termed here the ‘Short chord’ configuration. As reported in [11], the tandem configuration with an air gap (blue curve) presents well-defined peaks of noise reduction at the low frequencies before the vortex shedding noise becomes dominant. The peaks of noise reduction closely occur at the non-dimensional frequencies of $fl_d/U_c = 1, 2, 3, ...$, where $l_d$ is the distance between the two leading edges and $U_c$ is the convection velocity ($U_c \approx 0.7U$). At those peak frequencies, the radiated noise is close to that with an effective shorter chord equal to $c_1$ (grey curve), which is generally weaker than the baseline airfoil of a larger chord yielding noise reductions of around 10 dB at low frequencies.

The main features of the noise reduction spectra described above do not remain the same when introducing a Kevlar fabric that bridges the gap between the two plates. It is shown in Fig. 3b that this configuration (red curve) does not present distinct peaks of noise reduction as in the case of the air gap. Instead, weaker broadband noise reductions are achieved practically over the whole spectra. Similar levels of noise reduction can be observed however between the ‘short chord’ and ‘tandem - Kevlar’ configurations in the mid-frequency range ($4 < fl_d/U_c < 7$). This is investigated next in Fig.4 by showing the noise directivity at the frequencies indicated by the vertical dashed lines in Fig. 3b.



(a)

(b)

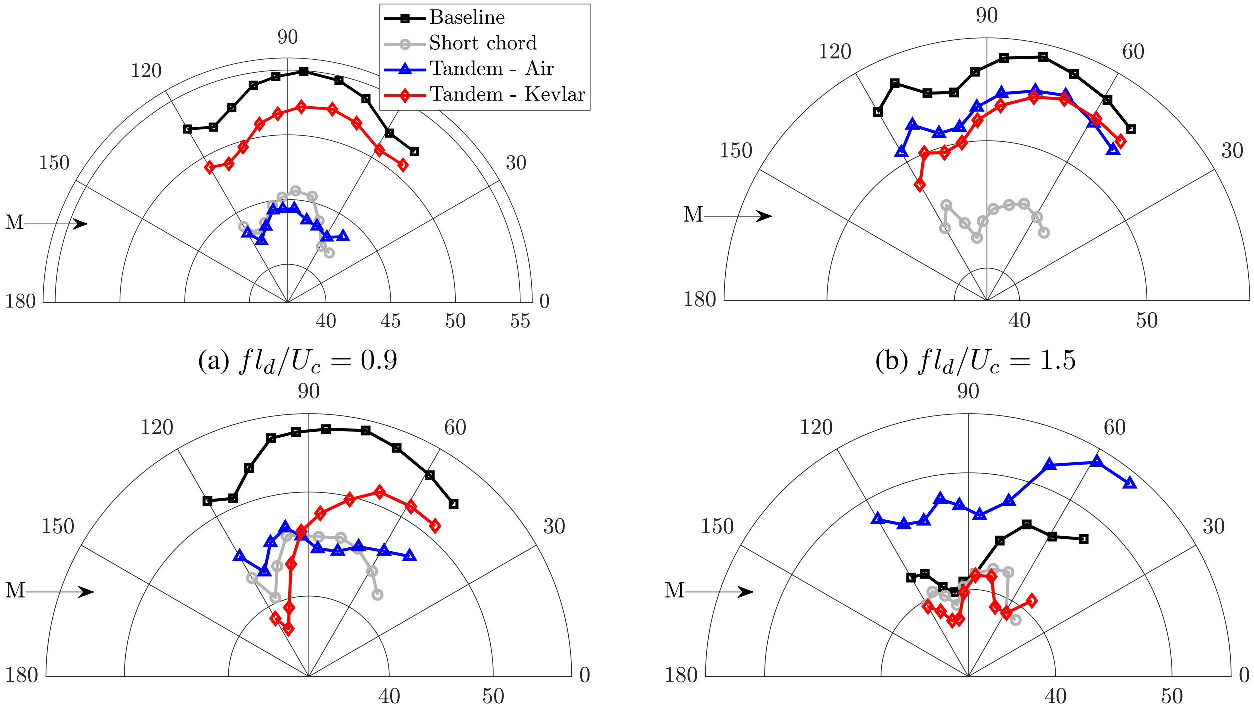
Figure 3: Comparison of the (a) Sound power spectra and (b) Sound power noise reduction spectra for $c_1/c_0 = 0.12$, $l/c_0 = 0.30$ and $U = 40$ m/s for various flat plate aerofoil configurations. Vertical dashed lines in (b): frequencies of the directivity plots in Fig.4.

The directivity of the noise radiated by the four configurations presented between Figs. 3a-3b is shown in Fig. 4 at different frequencies. The main features at each frequency are summarised below;

- At the frequency $fl_d/U_c \approx 0.9$ of the first peak of noise reduction of the ‘Tandem-air’ configuration (Fig. 4a), the radiation of this case is almost identical to that of only the upstream plate in isolation (‘Short chord’). The addition of the Kevlar fabric makes this configuration less effective at reducing noise at this frequency, although around 2 dB of noise reduction was still measured.
- At the frequency $fl_d/U_c \approx 1.5$ of the first deep of noise reduction of the ‘Tandem-air’ configuration (Fig. 4b), the radiation of these two tandem configurations with or without Kevlar are similar and have the same directivity pattern than the baseline. Both cases however show some 3 dB of noise reduction and up to 4-6 dB in the forward arc.
- At the frequency $fl_d/U_c \approx 2.1$ of the second peak of noise reduction of the ‘Tandem-air’ config-

uration (Fig. 4c), the radiation in this case is again very similar to the ‘Short chord’. This is now also true for the tandem case with Kevlar fabric in the forward arc.

- At the frequency $fl_d/U_c \approx 5.2$ (Fig. 4d) the directivity of the ‘Tandem-air’ configuration is already dominated by the interaction of the vortex shedding with the downstream leading edge. However, the results for the tandem configuration with the Kevlar fabric are very close to those of the short chord configuration both in magnitude and shape.



(a) $fl_d/U_c = 0.9$

(b) $fl_d/U_c = 1.5$

(c) $fl_d/U_c = 2.1$

(d) $fl_d/U_c = 5.2$

Figure 4: Comparison of the (a) Sound power spectra and (b) Sound power noise reduction spectra for $c_1/c_0 = 0.12$, $l/c_0 = 0.30$ and $U = 40$ m/s for a baseline flat plate aerofoil, a short chord ($c_0 = c_1$) and tandem configurations with an air gap and Kevlar fabric.

## 4. On the noise reductions of aerofoils with Kevlar-covered air gaps

In this section, we discuss some of the potential mechanisms of noise reductions in tandem configurations with Kevlar fabrics and the relation with the results shown in Section 3. It is useful to recall here some of the properties that have led to the choice of Kevlar fabric for this study. Kevlar has now been used for over a decade in hybrid anechoic wind tunnels. Tensioned Kevlar walls in the test section are considered ‘acoustic windows’ separating the flow field inside the tunnel and the surrounding anechoic chamber housing microphone arrays. Kevlar fabrics have been found to present a low transmission loss below 20 kHz, and hence often called ‘acoustically transparent’, while they are almost impervious to flow [12]. The use of Kevlar fabrics in tandem flat plates had therefore the potential to suppress the noise radiated from the downstream leading edge while maintaining the benefit of weaker radiation from the first chord with $c = c_1$ relative to the baseline with a larger chord $c = c_0$.

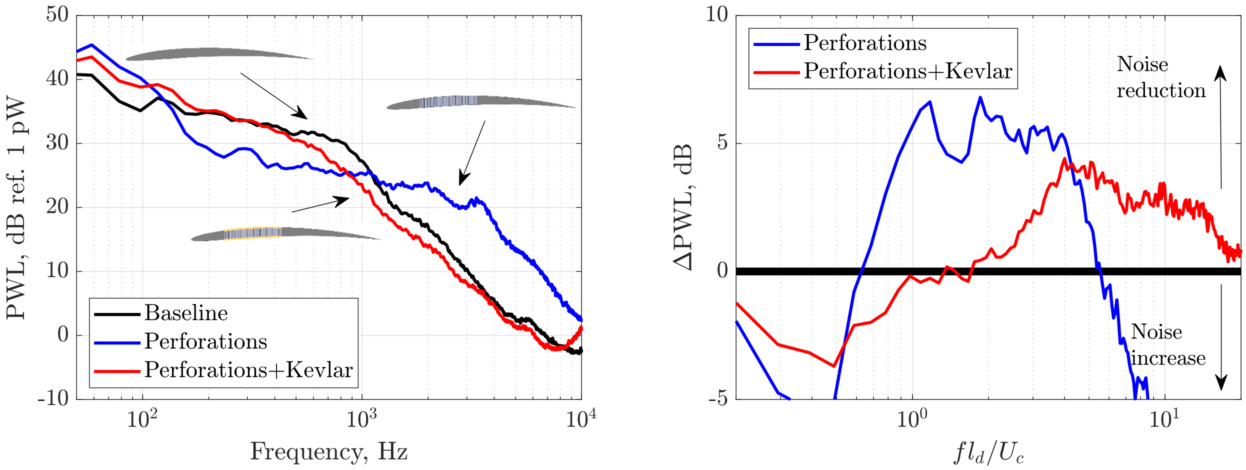
The following considerations on the potential mechanisms of noise reductions in tandem configurations with Kevlar fabrics are only preliminary and build upon the recent investigation of the authors for the case of downstream porosity and tandem flat plates [11]. The main points are summarised below;

- Interaction of the first leading edge with the free stream turbulence induces a pressure jump that propagates along the plate. In the case of tandem plates with an air gap, the discontinuity at $c = c_1$ behaves like a trailing edge since a pressure jump across the air gap cannot be supported. Therefore, the radiation from this upstream section occurs with an effective chord equal to $c_1$, which is generally weaker than the baseline airfoil of a larger chord. This might also apply to the cases with a Kevlar fabric between the plates, in line with the similar behaviour in directivity with the short chord case at some frequencies shown in Fig. 4. The degree of permeability of the Kevlar fabric and its membrane-like behaviour will most likely influence this effect, which seems to be frequency-dependent.
- It was hypothesised in [11] that a secondary vortex is induced at the first leading edge in response to the impinging vortex. For the cases with downstream porosity, the secondary vortex is assumed to interact with the porous section to generate a pressure jump that propagates at the convection speed $U_c$ across the porous section. Since the propagation speed $U_c$ is lower than the speed of sound $a$, radiation from this section is essentially 'cut-off'. This mechanism might be weak in the cases with Kevlar fabrics due to (1) its low porosity (2-8%) and reportedly low interaction with the turbulence-related hydrodynamic pressure field [12] and (2) modified characteristics in withstanding a pressure jump due to its membrane-like behaviour.
- It was further assumed that when the secondary vortex interacts with the second leading edge it induces a pressure jump with a phase inversion of $180^\circ$ relative to the first leading edge. The phase inversion was attributed to the opposite sense of rotation of the secondary vortex relative to the initial impinging vortex. This interference source contributes to the distinct peaks of noise reduction in the 'Tandem-air' configuration at the non-dimensional frequencies $fl_d/U_c = n$ observed in Fig. 3b. These peaks are however not present for the case with the Kevlar fabric, which might indicate that the secondary vertex can no longer interact with the second leading edge.

## 5. Kevlar-covered downstream porosity on a thin aerofoil

In this section, we investigate the use of Kevlar fabric to enhance the noise reduction performance of downstream porosity in thin aerofoils. It is envisaged that the use of Kevlar fabric could potentially also improve the aerodynamic performance due to its low flow permeability. Downstream porosity was reported in [11] to be able to yield noise reductions of up to 8dB on realistic thin aerofoils for OGV applications at some frequencies and up to 2.8dB reduction in overall noise. An increase in noise was however observed both at low and high frequencies when testing the aerofoil at a non-zero angle of attack, which was found to be related to an increase in self-noise. The increased self-noise at low frequencies was related to a thicker boundary layer on the suction side of the aerofoil. This behaviour was attributed to flow feeding the boundary layer through the holes driven by the pressure difference across the aerofoil. Results are therefore shown here only for the largest geometric angle of attack AoA=15° tested in this investigation, which is the most critical case where the Kevlar fabric can yield the most benefits.

The sound power spectra measured for a NACA4505 aerofoil with a baseline leading edge, treated with downstream porosity (perforations) and with Kevlar-covered downstream porosity are compared in Fig. 5a. The same data is shown in the form of noise reduction spectra in Fig. 5b. The downstream porosity treatment without any Kevlar covering (blue curve) yields up to 7 dB of noise reduction but results in noise increase both at low (<130 Hz) and high (<1000 Hz) frequencies as previously reported. The introduction of the Kevlar fabric (red curve) is however capable of suppressing the noise increase at the higher frequencies, often attributed to roughness noise, and even reducing noise by 2-3 dB at those frequencies. The low frequency noise is however not fully suppressed, which suggests that the Kevlar fabric is not able to completely prevent flow feeding the boundary layer in the suction side of the aerofoil through the perforations. The inferior noise reduction performance of the configuration with Kevlar between $130 < f < 1000$ Hz results in lower overall noise reductions for this AoA, as shown in Table 2. However, at lower AoA there is a clear benefit of the Kevlar treatment in terms of OAPWL noise reductions. Furthermore, it is expected that the smooth surface of the Kevlar fabric and its level of permeability would reduce drag and minimise lift losses relative to the treatment with bare perforations.



(a) (b)

Figure 5: Comparison of the (a) Sound power spectra and (b) Sound power noise reduction spectra for $c_1/c_0 = 0.12$, $l/c_0 = 0.30$, $U = 20$ m/s and AoA = 15° for NACA4505 aerofoils with untreated LE, downstream porosity and Kevlar-covered perforations.

Table 2: Reductions in OAPWL (dB) with $l_0/c_0 = 0.12$ and $l/c_0 = 0.30$ at $U$=20 m/s.

| | AoA(°) | | | |
|---|---|---|---|---|
| Treatment | 0 | 5 | 10 | 15 |
| Perforations | 0.5 | -0.7 | -0.1 | 1.3 |
| Perforations+Kevlar | 1.5 | 1.4 | 0.9 | 0.5 |

## 6. Conclusions

This work has investigated the reduction of turbulence-aerofoil interaction noise by using a Kevlar section downstream of the aerofoil leading edge. When the treatment is applied on flat plates at zero angle of attack it has been found to yield noise reductions over practically all frequencies with up to 7 dB of noise reduction at some frequencies. The Kevlar fabric is also applied on a thin NACA4505 aerofoil with downstream porosity. It has been found that the treatment is capable of suppressing the increase in self-noise at high frequencies characteristic of untreated porous sections and mitigating the low frequency noise at 'high' AoA attributed to cross-flow through the perforations. The noise reduction mechanism of Kevlar fabrics is still not fully understood but has been discussed that it can be related to an effective shortening of the chord and/or a cut-off effect over the Kevlar section which depends upon the permeability of the Kevlar fabric and its membrane-like behaviour. Further work is planned to better understand these mechanisms and to fully assess the impact of the Kevlar treatments on the aerodynamic performance. However, the results presented in this paper indicate that this technology can achieve significant levels of noise reduction with potentially minimal impact on aerodynamic performance.

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