Influence of the liner-type treatment on the trailing-edge noise generated by a flat plate

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Abstract
Several liner-type treatments (three different rectangular grooves covered by three different low porosity wire-mesh screens) on the trailing edge of a flat plate have been investigated in the anechoic wind-tunnel of Université de Sherbrooke. Far-field acoustic directivity measurements have been achieved at Reynolds numbers based on the plate length from $7.3 \times 10^5$ to $1.7 \times 10^6$, yielding radiation maps of all possible liner combinations that are then compared to the reference solid flat plate and to the plate with inserts alone. Noise from the flat plate corresponds to dipolar trailing-edge scattering with an extra shallow hump attributed to the unsteady flow recirculation behind the thick plate. When grooves are added, the latter contribution is amplified and additional cavity noise is observed with several tones and humps. The tones are shown to be resonance between high order modified Rossiter modes and cavity depthwise modes. The hump is a combination of drag dipoles and cavity monopoles from the groove row. The addition of screens always reduces the amplification of the dipolar edge scattering but exhibits very different non-linear responses for the cavity noise. The combination screen with the smallest cells and the insert with the shallowest cavities (corresponding to the same type of treatment applied previously on the Controlled-Diffusion airfoil) yields the lowest levels overall, while the screen with intermediate cell size almost always triggers noise amplification and the screen with a coarse mesh has an intermediate behavior. At high frequencies, the previously reported roughness noise is also observed.

Keywords
Liner-type acoustic treatments, trailing-edge noise, flat plate, cavity noise, acoustic measurements

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Introduction

Airfoil trailing-edge noise or self-noise is a problem involved in many engineering applications such as wind turbines, cooling systems and drones. The sound is generated by the scattering of turbulent boundary-layer disturbances at the trailing edge and such a phenomenon could yield tonal or broadband noise signature depending on the operating conditions such as Reynolds number and angle of attack. This noise mechanism has been widely investigated because of the wide usage of the aforementioned devices in our everyday life. Regulation to limit noise pollution encourages companies and scientists to look for effective noise reduction methods. Several solutions for the trailing-edge noise attenuation (serrations, porosities, surface treatments) have been proposed.

For instance, serrations inspired by the structure of the Owls wing were theoretically investigated by Howe and the proposed model showed a potential significant trailing-edge noise reduction. Numerous experimental, analytical and numerical studies have been conducted over the years, yielding new shapes with some significant noise reduction mostly at high frequencies. Even true shape optimization of such passive devices on an industrial airfoil have been recently achieved.

As an alternative to serrations, porous treatments on the trailing edge have been drawing a lot of attention for the past decade. Such a treatment based on foam-like, open-cells materials and applied to airfoils was investigated by Geyer and Sarradj. The higher noise attenuation by the materials with high air flow resistivity was demonstrated. Hot-wire measurements also showed the decrease of lift with the decrease of air flow resistivity and the increase of the porous extent. Moreover, some porous materials were found to even increase noise compared with the reference configuration. That effect was attributed to the surface roughness, porosity and possible vibrations of the trailing edge. The importance of the open cell metal foam permeability on the noise reduction was investigated from both acoustical and aerodynamic points of view by Rubio Carpio et al. The most permeable treatments introduced in the last 20% of the airfoil chord showed up to 10 dB noise attenuation compared with the reference solid configuration at Strouhal numbers based on the chord and the free-stream velocity below 16. At high frequencies the porous treatments increase the trailing-edge noise due to the roughness effect. The reduction of the acoustic impedance jump by the cross-flow through the permeable treatments was also demonstrated along with its effect on the broadband noise attenuation. This conclusion is in line with the previous study of Herr et al. where the blocking of one of the porous treatment side lead to elimination of the noise reduction effect. Rubio Carpio et al. also reported an increase of the velocity deficit and surface drag for the four metallic foam porous treatments. However, the detailed explanation of the noise reduction mechanism by the porous materials was not provided, because of the difficulty of instrumentation of the porous section without changes of the material characteristics and flow in the pores. The numerical replication of the experimental study of Rubio Carpio et al. was performed with the lattice-Boltzmann method by Teruna et al. They confirmed the noise reduction up to 9 dB compared with the solid configuration at low frequencies. They also found the distribution of the noise sources along the porous area, which meant acoustic scattering at multiple locations. The surface pressure fluctuations were also reported not to be significantly affected by the porous medium. However, the porous medium was modelled as a homogenous porous section taking into account the material porosity with Darcy's law due to the computational cost, and the internal topology of the porous treatment was not considered. Showkat Ali et al. presented
an investigation for the simplified configuration of a flat plate with the blunt trailing-edge metallic-foam treatments to avoid complex physics of the flow as in the present experiment. The acoustic and aerodynamic measurements evidenced the reduction of flow acceleration over the trailing edge, split-up of the large coherent structures in the wake as well as fading of the vortex shedding. Note that all the above examples involve non-locally reacting surface treatments.

Perforated trailing edges were also studied as one of the porous treatments types by Rubio Carpio et al.\textsuperscript{16} The trailing-edge appendices were 3 D-printed with straight cylindrical channels connecting the two sides of the NACA-0018 airfoil. Several distances between channels were tested to control the permeability of the treatment. The abatement of the broadband noise was observed and compared with the metallic foams treatment. Rubio Carpio et al.\textsuperscript{16} then concluded that, to achieve similar attenuation level, the permeability of the perforated trailing edge should be at least three times higher than that of the foam-type treatment. Therefore, they assumed that the inner structure of the porous treatments influences the noise reduction besides the permeability.

Overall, all the studies about trailing-edge porous treatments have been carried out for different geometries with various percentages of the treated area and diverse instrumentation. Subsequently, there are still some doubts about the optimal length of the treated area to provide the most effective noise reduction with a minimal influence on the loading and the actual mechanisms behind the noise reduction achieved by the porous treatments. Another obstacle is the manufacturing of the porous materials and the geometrical repeatability of the tested samples. For better understanding of the noise attenuation mechanisms, the resistivity and permeability of the materials need to be fully controlled for instance. Moreover, despite the promising results of the noise attenuation by some of the above porous materials, remaining disadvantages like loading losses, the complexity of the implementation and production of the treatments motivate further research on different new solutions.

Another passive treatment for noise mitigation widely employed for aircraft engine nacelles are acoustic liners. It has been applied for slat noise reduction.\textsuperscript{17–19} In the experimental work of Smith et al.\textsuperscript{18} the honeycomb liners were mounted on the both slat cove and main wing leading edge. The noise attenuation up to 2.5 dB was demonstrated. A significant drop of performance was however reported as well. Smith et al. attributed it mostly to the manufacturing problems rather than to the difficulty with applying the liners. Following work published by Casalino et al.\textsuperscript{19} was aimed at optimizing the single slotted flap and a maximum noise reduction of 6.4 dB was achieved. It was shown that the liners were effective up to frequency about 1 kHz. However, to the authors’ knowledge the number of studies on airfoil noise reduction by acoustic liners is still limited.

Recently, an industrial Controlled-Diffusion (CD) airfoil, which has been used for compressor and turbofan applications, aerospace and automotive ventilation systems, was investigated for Reynolds numbers from $8.5 \times 10^4$ to $3.5 \times 10^5$ at Université de Sherbrooke. Several trailing-edge treatments on the last 10% of the chord length, among them serrations and liner-type porous treatments were compared with a reference configuration.\textsuperscript{20} The liner-type porous treatment was built with several rows of cavities covered by different wire-mesh screens and had a solid skeleton to prevent any communication between the two sides of the airfoil to preserve the airfoil loading. Far-field and wall-pressure measurements have been complemented with hot-wire anemometry. A complete description of the experiments can be found in Moreau et al.\textsuperscript{20} One of the main conclusions of this study was that the liner-type
treatment shows significant noise reduction on a wide frequency range without loading penalty when a highly permeable screen was used as found above by Rubio Carpio et al.\textsuperscript{13} (and contrarily to Geyer and Sarradj’s findings).

However, the detailed investigation of the influence of the geometrical parameters such as depth of cavities and porosity of the screen could not be achieved because of the small scale of the airfoil trailing edge. Therefore, it was decided to study the aforementioned geometrical parameters on the simplified case of a flat plate at a bigger scale. This configuration also removes the additional effect of the mean adverse pressure gradient on the noise generation and mitigation.

The outline of the article is as follows. Firstly, the experimental setup including the mock-ups and measurement systems is described. Secondly, the acoustic results for the reference configuration are presented and the noise sources on the flat plate are identified. Thirdly, an influence of the cavity depth on the far-field noise signature is presented, which constitutes one of the contributions of the present work. An analysis of the effect of different wire-meshes then follows. Finally, the conclusion summarizes the findings on the influence of the geometrical parameters of the liner-type treatments on the trailing-edge noise generation.

**Experimental setup**

The acoustic measurements have been performed for a flat plate with liner-type trailing-edge treatments in the open-jet anechoic wind tunnel of the Université de Sherbrooke. The flow velocities in this facility range from 5 m/s to 40 m/s in a nozzle section of 30 cm height and 50 cm width. The exit flow is uniform with a low residual turbulence intensity below 0.4\%.\textsuperscript{21} The flow velocity is controlled by two radial fans, and the temperature of the flow is maintained at 21°C. To understand the effect of the geometrical parameters of the liner-type treatments on the noise generation, directivity measurements at various flow regimes have been conducted. The following section describes the mock-ups and the experimental setup.

**Flat plate mock-ups**

A sketch of the flat plate mock-up is shown in Figure 1. The flat plate has a 71 cm width, a 73.8 cm length and a thickness $e$ of 2.96 cm. It is mounted at the exit of the nozzle so that the interior wall of the nozzle coincides with the surface of the flat plate. The gap at the junction is covered by a thin aluminum tape to minimize the disturbances of the boundary layer and to make the transition as smooth as possible. The last 20 cm of the trailing edge of the plate are replaceable inserts with several liner-type treatments. Each insert consists of 10 rows of cavities and ends with a square trailing edge. Three inserts with a cavity width ($L$) of 10 mm and depth ($D$) of 10 mm (I1), 5.38 mm (I2) and 3.3 mm (I3) are used. Only the shallower cavity was used before on the CD airfoil. Cavities can be covered by some wire-mesh screen, which is fixed on top of the insert by a metallic frame and some screws. Based on the CD airfoil experience,\textsuperscript{20} three screens with different porosity but low specific airflow resistance or resistivity ($\approx$1 Rayl) are tested in various combinations with inserts. The cell sizes equal to 0.75 mm, 1 mm and 5 mm with the wire diameter of 0.25 mm, 0.4 mm and 1 mm correspond to the first (S1), second (S2) and third (S3) screens respectively. The treatment is mounted so that the screen is flushed with the main body surface. The geometrical parameters of the investigated treatments are summarized in Table 1.
The directivity measurements have been carried out by an arc instrumented by 12 PCB 378B02 piezotronics 1/2" microphones that are located at the distance of 1 m from the trailing edge of the flat plate (see Figure 2). The center of the arc coincides with the trailing edge at the half-width of the plate. The microphones are distributed from 60° (microphone 12) to 142.5° (microphone 1) with a step of 7.5°. Microphone 8 is located above the trailing edge and corresponds to 90°. The microphones were calibrated by the B&K pistonphone type 4228 with calibration accuracy ± 0.2 dB. The flow velocities ($U_\infty$) vary from 15 m/s to 35 m/s with a step of 5 m/s. As shown in Jaiswal et al., the uncertainty of the tunnel inlet velocity is 1% of $U_\infty$. Yet, below 15 m/s, the jet became less stable depending on the plate surface roughness. The corresponding range of Reynolds numbers based on the plate length is from $7.3 \times 10^5$ to $1.7 \times 10^6$. For each case the signal has been registered during 30 s with a sampling frequency of 51200 Hz.

### Aerodynamic measurements

In parallel to the above acoustic measurements, several flow investigations have been performed. Flow measurements have been achieved either by hot-wire anemometry (HWA) or by planar (2D-2C) Particle Image Velocimetry (PIV) to yield additional information about
the flow upstream or above the plate treatment. The details of the HWA and the PIV setups are given by Yakhina et al.\textsuperscript{23}

First, a flow visualisation with a mixture of talc powder and isopropyl alcohol has been conducted to verify the two dimensional nature of the flow as shown in Figure 3. All the streamlines remain parallel and the flow is aligned with the incoming direction perpendicular to the plate trailing edge. Therefore, focusing the microphones in the mid-span plane of the plate is justified.

Figure 4 shows the mean velocity profiles $U$ and root-mean-square (rms) of the axial velocity fluctuations $urms$ at the distance of 1 cm upstream from the junction for the lowest tested Reynolds number. The mean $U$ profiles measured by HWA and by PIV are compared with the theoretical profiles for laminar and turbulent boundary layers.\textsuperscript{24} Both measured $U$ profiles are close to each other and their shape is similar to the profile of the turbulent boundary layer obtained by $1/7\theta h$ law. The rms profiles measured by HWA and by PIV are compared with the Direct Numerical Simulation of Spalart\textsuperscript{25} at a similar Reynolds number based on the momentum thickness, $Re_0 \simeq 1400$. $urms$ fluctuations measured by PIV have the highest levels and a similar shape to the DNS data. As noted by Hutchins et al.\textsuperscript{26} the lack of primary peak in $urms$ in the HWA is caused by the simultaneous competing effects of the Reynolds number and viscous-scaled wire length $l^+$, which is beyond the recommended value of 20 here. Yet, both measurements confirm that the boundary layer is turbulent upstream of the treated region for all investigated speeds.

Finally, some measurements have been achieved above and near the trailing edge of the plate. The contours of mean axial velocity ($U$), root-mean-square axial velocity ($urms$) and root-mean-square wall-normal velocity ($v rms$) obtained by planar PIV measurements are shown in Figure 5. The recirculating zone after the blunt trailing edge is clearly observed, with some significant fluctuations near the edge, suggesting an unsteady breathing bubble.
Acoustic results

In the following sections the acoustic results for the reference case, configurations with inserts only and with combination of inserts and screens are presented and analyzed. All spectra are presented for the microphone 8 which is perpendicular and above the trailing edge of the plate. The frequency resolution of the spectrum is 2 Hz.

Test-retest reliability has been achieved by comparing sets of experiments where the flat plate has been dismantled from the wind tunnel (exp.3) and also between different days within the same set of experiments (exp.1 and exp.2), in order to provide some further uncertainty quantification on the presented measurements. Figure 6 presents the comparison between the two sets of experiments carried out with a delay of a few months. Good overall repeatability of the acoustic measurements for all configurations is found between day-to-day experiments and different sets of experiments. In general the SPL of the first experiment (exp.1) at frequencies below 300 Hz is slightly lower for all configurations and speeds (about 1 dB). It is most likely caused by the flow velocity uncertainty. For the reference configuration (Figure 6(a)), exp.3 at 15 m/s reaches the background noise of the anechoic wind tunnel at about $-20$ dB. The limited sensitivity of the microphone used in exp.1 and 2. explains the plateau observed at -10 dB. Moreover, even in exp.3 at 15 m/s, several tones can be observed at frequencies beyond 1 kHz which are caused by the
electromagnetic contamination of the setup. Therefore, no further data are given below 
\(-10\) dB. The largest variations in the measurements (about 2 dB) have been obtained for
the deepest cavities (Figure 6(b) and (c)) almost at all frequencies. Noticeably, when the
cavities are covered by screens at frequencies beyond 2 kHz some discrepancy in the peaks
between experiments are observed. This could most likely be traced to the positioning and
fixation of the screens on the mock-up. Therefore, an overall maximum uncertainty of 2 dB
can be attributed to the present experimental set-up.

Reference configuration

The sound pressure levels at 90° (microphone 8) above the plate trailing edge are shown in
Figure 7 for the reference configuration without treatment at various flow velocities. At
15 m/s several tones caused by electronic noise are detected as mentioned above. Three
different regions of the spectra can be identified: before 400 Hz, between 700 Hz and
5.5 kHz and beyond 5.5 kHz. At 1 kHz a shallow hump can be observed for the highest
velocities, the size of which increases with the speed and also shifts to higher frequencies. In
Figure 7(b) the acoustic pressure is normalized by \(U^2_e\) and scaled with Strouhal number
\(St_e \equiv f U_e / e\) (where \(f\) is frequency) based on the flat plate thickness \(e\) to highlight the
mechanism of the noise generation. The humps observed at 1 kHz for high flow velocities collapse at Strouhal number equals 1 and stress that the source is most likely the recirculating area generated after the blunt trailing edge as was shown in Figure 5. Moreover, all spectra coincide with each other up to Strouhal number equals 1. Note that Sanjose et al. also showed that this middle region of the spectrum collapses well with Amiet’s trailing edge noise prediction. At low frequencies, for Strouhal number below 0.1, the scaling with $U_7$ starts collapsing the spectra in Figure 7(c) which is a sign of the increasing jet self-noise contribution. Yet, the excellent collapse seen in Figure 7(b) over a large frequency range stresses the dominant dipolar nature of the jet-plate interaction.

**Configurations with inserts only**

Figure 8 shows the sound pressure level for different tested inserts. In Figure 8(a) the configuration with insert 1 shows a hump that starts at 300 Hz for 15 m/s and shifts toward higher frequencies around 1 kHz with the increase of the flow velocities. This hump was hardly observed for the reference configuration and can be attributed to the flow recirculation behind the blunt trailing edge. At frequencies beyond 2 kHz, the spectra for all flow velocities have very similar shapes and have no shift with the increase of velocity. Such features as two humps centered at 3 kHz and 6.5 kHz and the peaks around 5 kHz are also distinguished. This area corresponds to the second noise source generated by the cavities. The cavity noise increases more drastically at high flow velocities and has comparable noise level with the hump generated by the trailing edge. Figure 8(b) and (c) shows that the spectra for the shallower inserts have similar behavior but with less pronounced features (humps and tones). Nevertheless, a clear tone around 7000 Hz can still be seen for insert 2. For insert 3 all the features have almost vanished in the broadband spectra. There is a possible coupling between the two noise sources so that the cavity depth affects the first hump as it is more defined for the configuration with deeper cavities. The similar effect was observed by Moreau et al. for the katana blade between the cavity noise induced by the blood grooves (or Shinogi-ji) and the vortex shedding induced by the blunt side of the single-sided sword. The comparison between the reference configuration and configurations with inserts at 15 m/s and 35 m/s is presented in Figure 9. The reference configuration has the lowest SPL and, as expected, the shallowest insert 3 is closest to the reference case. In the frequency range from 1 kHz up to 8 kHz the shapes of the spectra for all three inserts at 35 m/s have the peaks and humps (the three regions highlighted by arrows) almost at the

**Figure 7.** (a) Sound pressure level for the reference configuration at various flow velocities; (b) sound pressure level normalised by $U_7^5$ and scaled with Strouhal number; (c) sound pressure level normalised by $U_7'$.
same frequencies. Note that the levels of the second and third humps clearly increase with the cavity depth. Even though this is less pronounced on the first hump, the constant increase of its levels with cavity depth stresses again the coupling between the trailing-edge scattering and the cavity noise. At the lowest speed (15 m/s), all humps have almost disappeared, suggesting as in Howe’s cavity model that the monopole contribution of the cavities has almost vanished (see Figures 3 and 4 in Howe32).

Different scaling methods are tested in an attempt to identify the noise sources in the presence of inserts. As an example, the insert with the deepest cavities is chosen due to the most defined evidence of different noise mechanisms. The scaling of the normalized acoustic pressure by $U_\infty^5$ with Strouhal number based on the plate thickness in Figure 10(a) presents a collapse of the spectra for Strouhal number up to 1.5. A clear dipolar radiation is therefore observed below this Strouhal number. This result is similar to the drag dipole discussed by Howe32 after analysis of the noise generation mechanism for the single shallow wall cavity at Mach numbers below 0.1 as in the present experiments. The hump around 1 kHz for all flow velocities appears at Strouhal number equals 1, which again pinpoints to the unsteady flow recirculation behind the thick plate trailing edge, yielding additional edge scattering. At high Strouhal number, two groups of spectra can be distinguished for low flow velocities (15 m/s and 20 m/s) and for high flow velocities (25 m/s to 35 m/s). Finally, for Strouhal number below 0.1, as noted by Moreau et al.,27 a collapse of the spectral levels with $U_\infty^7$ stresses the quadrupolar jet contribution, as for the reference case. Such a frequency range is therefore again discarded.

Figure 10(b) shows the scaling of the normalized acoustic pressure by $U_\infty^6$ with Helmholtz number based on the cavity depth ($He = kD$). It collapses the spectra for Helmholtz below 0.1, confirming the aforementioned dipolar radiation at lowest frequencies. At high Helmholtz number, the plotted spectra can be divided into two groups again. The spectra for high flow velocities (25 m/s, 30 m/s and 35 m/s) coincide almost perfectly while the spectra at low velocities have differences in levels and shapes. The possible reason is that with the increase of the flow velocities the state of the shear layers above the cavities changes. Moreover, as already mentioned in Figure 9, the increasing hump with increasing velocity around a Helmholtz number of 1.25 should also be traced to the increasing contribution of the monopole contribution of the cavity noise as noted by Howe.32 The tones at high frequencies are observed at Helmholtz numbers equals 0.9 and 1 and coincide for all flow velocities. Similarly, the third hump seen in Figure 9 is now centered around a
Both results emphasize that, for the deep grooves, clear cavity modes based on depth can be identified. Given the low velocity of the present experiment, the aforementioned tones can be associated with the Rossiter modes \( n = 3 \) (or \( n = 2 \)) observed by Block yielding weak tones over a broader hump for a similar cavity (bottom right plot in Figure 5 in Block\textsuperscript{33}). To verify this assertion, the model for a rectangular cavity in air proposed by Block is used here. She proposed a modification of the model given by Rossiter for the feedback loop between the opposite edges of the cavity and gave the following expression for the Strouhal number based on the cavity length \( L \) and depth \( D \):

\[
St_B^L = \frac{fL}{U_\infty} = \frac{n}{k_r + M_\infty(1 + 0.514L/D)}
\]  

(1)

where \( L \) and \( D \) equals 0.01 m for the present case with insert 1, \( n \) is the mode number, \( k_r \) is the wavenumber of the disturbance travelling downstream and \( M_\infty \) is the flow Mach number. Note that the original Rossiter model reads
and does not involve the cavity aspect ratio $L/D$. Block also considered the depthwise modes that are given by the following formula for the same Strouhal number:

$$S_{L}^{D} = \frac{1}{M_{\infty}} \frac{L}{D} \left( \frac{0.75}{1 + A(L/D)^{B}} \right)$$

(3)

where $A$ and $B$ have empirical values of 0.65 and 0.75 respectively. Equations (1) and (3) yield the frequencies at which oscillations occur in the lengthwise and depthwise modes respectively. Each oscillation is reinforced by the other at a given Mach number where these dimensionless frequencies coincide. Both frequencies are shown in Figure 10(c) by solid lines along with the original Rossiter model given by equation (2) and presented by dashed lines. The experimental symbols correspond to the Strouhal and Mach numbers calculated for the frequency of 5 kHz where the tones are observed in Figure 8(a). The experimental results lie exactly on the depthwise mode line and also correspond to the intersection of lengthwise modes greater than 3 as was also observed by Block. A similar plot can be obtained for insert 2 but this time at 7000 Hz and modes greater than 4 are now excited. This emphasizes the resonance between the two modes for the deepest cavities.

Finally, the angle-frequency directivity plots with different inserts are presented in Figure 11 at 35 m/s for several frequency ranges corresponding to the regions identified in Figure 9. In all frequency ranges, insert 3 generates less noise compared to deeper inserts. The first range from 800 Hz to 1.5 kHz corresponds to the hump generated by the recirculating area after the blunt trailing edge. The mean SPLs for insert 1 and insert 2 coincide behind the trailing edge (from 60° to 82.5°). Above the flat plate (from 90° to 142.5°) insert 1 has higher levels by 2 dB compared to insert 2. These slight increases of levels with inserts are again showing the coupling between edge and cavity noise. Two lobes can be distinguished for all configurations with the upstream increase of the SPL, which is typical of a dipolar source. A similar directivity has been found by Howe when the drag dipole dominates (lower Strouhal numbers 0.5 and 1 in Figure 5 in Howe) and the unbalance of the upstream and downstream lobes can be attributed to the Doppler amplification by the mean flow. At higher frequencies the differences between insert 1 and insert 2 become more significant due to the strong cavity noise contribution as already noted in the spectra in Figure 9. Yet, two distinct behaviors can be observed in Figure 11(b) and (c). In the former, the downstream lobe is now as large or larger than the upstream one. In the latter, the larger upstream lobe observed in Figure 11(a) is recovered but now multiple lobes can be identified on the maps, at least for insert 1. The additional lobes observed beyond 5 kHz (which corresponds to a Helmholtz number based on the plate length of 1) show that the plate is no longer compact, and the trailing-edge noise directivity exhibits additional lobes. In the range from 2 kHz to 5 kHz, the significant increase of the downstream lobe with increasing cavity depth can be most likely related to the more significant contribution of the monopole part of the cavity noise as already observed by Howe (higher Strouhal numbers 2 and 2.5 in Figure 5 in Howe) To further verify this assumption, Figure 12 shows the directivity plot of insert 1 (deepest cavity) at several discrete frequencies around the resonant tone observed at 5 kHz in Figure 8(a). The downstream lobe is indeed
seen to dominate at 4 and 5 kHz, while the upstream lobe is dominant at lower and higher frequencies. Starting at 5 kHz, the additional lobes caused by the lack of compactness are also seen. Note that, when the single cavity model of Howe32 is adapted to the present geometrical parameters of the cavity and that the resonant Strouhal number is tuned to the third Rossiter mode (as observed in Figure 10(c)), the monopole term is seen around and below the resonant frequency of 5 kHz.

**Influence of the screen**

As a next step, three different wire-mesh screens have been added on top of each insert. These configurations have been compared with the reference flat plate and the configurations with the three inserts described above. The SPL spectra at 15 m/s and 35 m/s are presented in Figure 13. At low frequencies (below 300–400 Hz) all configurations make similar noise. At 15 m/s, the configuration with insert 1 and screen 3 has 2 dB higher SPL at frequencies up to 300 Hz, which is most likely caused by the aforementioned uncertainty in the flow velocity for this case. Note that screen 3 induces a roughness on the plate that increases the excitation of the jet even more. Between 400 Hz and 1.5 kHz, all screens at both velocities reduce the hump associated with the recirculating area as can be clearly seen for the insert 1 with deepest cavities in Figure 13(a). Yet, up to 1 kHz the levels of most configurations with screens remain close to the reference one without treatments, especially with increasing velocity. At higher frequencies, beyond 2 kHz where the cavity noise is mostly generated, the effect of the screen is less clear and may only reduce this noise source in some frequency range. For instance, in the case of insert 1, screen 1 generates less noise at frequencies from 2 kHz to 6 kHz whereas screen 3 is the noisiest one for the same frequency range. The combination of the shallowest cavities of insert 3 and screen 1 with the finest mesh produces less noise at the aforementioned frequency range compared with the other two screens. Actually, the combination of insert 3 with screen 1 (the exact same features as in the CD airfoil) at 15 m/s is the only configuration in the whole test matrix that shows a consistent overall noise reduction compared to the configuration with insert in all directions at all frequencies, with maximum gains up to 10 dB. Moreover, the screens may also amplify the noise level. For instance, screen 2 with a middle-range cell size generates an additional hump from 2.5 kHz to 5 kHz at both speeds. At 35 m/s, it also amplifies the hump around 6.5 kHz associated with cavity noise by several decibels. As pointed out by Soderman,37 the screened cavities may yield additional resonance caused by vortex shedding at the cell orifices. In general, the configurations with screens at 15 m/s have similar SPL and spectra shape depending on the insert. At 35 m/s the influence of the screen leads to more significant discrepancies at high frequencies. With increasing speed or
Reynolds numbers the patterns in the radiations maps do not change but the noise gains are reduced and the noise generation are increased. This observed noise amplification by the screens with increasing Reynolds number can be caused by the surface roughness of the treatments as was already mentioned for instance by Geyer & Sarradj\textsuperscript{11,12} or Rubio Carpio et al.\textsuperscript{13} for various foam-type porous trailing edges.

**Figure 12.** The angle-frequency directivity plot at discrete frequencies for insert 1 at 35 m/s. (a) Insert 1 at 15 m/s. (b) Insert 2 at 15 m/s. (c) Insert 3 at 15 m/s. (d) Insert 1 at 35 m/s. (e) Insert 2 at 35 m/s. (f) Insert 3 at 35 m/s.

**Figure 13.** Sound pressure level for the reference configuration and the configurations with inserts and screens at 15 m/s and 35 m/s.
As the configuration of the shallowest insert 3 combined with different screens generates less noise compared to other inserts it was chosen to illustrate the angle-frequency directivity plot shown in Figure 14. In the first frequency range from 800 Hz to 1.5 kHz where the hump caused by the trailing-edge recirculating area was identified, screens 1 and 2 have very similar SPL while screen 3 produces SPL 2 dB higher. The overall levels of the first two screens are then slightly lower than for the insert alone (Figure 11(a)) consistently with the spectra in Figure 13. The overall shape of the directivity pattern is also close to the one which was observed previously for the configuration with insert only, corresponding to the drag dipole. In the second frequency range (2–5 kHz), several noticeable changes compared to the case without screen can be identified. Downstream, screen 2 has almost identical levels (same monopole contribution). Screen 3, however, exhibits a much larger upstream lobe compared to the case without screen (almost similar to the deepest cavity of insert 1), stressing a larger monopole contribution (Figure 11(b)). Only screen 1 yields some noticeable noise reduction of the monopole contribution. Upstream, screens 2 and 3 significantly amplify the cavity noise radiation and yield similar levels. Screen 2 still generates the highest SPL almost for all microphones except at 142.5° and 135° where screen 3 has slightly higher noise. However, screen 1 again yields a significant reduction of the upstream noise contribution, and overall recovers a more dipolar directivity. From 5 kHz to 8 kHz screen 2 produces the highest SPL except for some upstream microphones. Screen 1 has again the lowest levels except for 4 microphones above the trailing edge, but within 1 dB of the SPLs of screen 3. Screen 3 has a higher level than screen 2 for upstream microphones and the lowest levels for the microphones above the trailing edge. Finally, note that a similar multi-lobe noise directivity as in the case without screen is observed, sign of the non-compactness of the plate.

In summary, on the one hand, screen 2 almost always amplifies the cavity noise, both monopolar and dipolar contributions. On the other hand, screen 1 has the overall lowest levels for all frequencies at almost all observation angles (within the measurement uncertainty), which is also consistent with the observation on the overall radiation map and the spectra. Yet, the noise reductions are smaller than at the lower speed, and are no longer always significant compared to the insert without screen. This best configuration I3S1 shares the same features as the CD airfoil: same cavity aspect ratio and same screen, which suggests a further detailed investigation is needed to decipher its noise reduction mechanism. Note also, that the second best configuration I3S3 is the closest combination that actually mimics the scaled trailing-edge treatment of the CD airfoil (number of cells per cavity length). This may actually suggest that the configuration tested on the CD airfoil could be still further improved. Yet, the fact that the intermediate screen S2 strongly changes the levels and the

![Figure 14. The angle – frequency directivity plots for insert 3 and all screens at 35 m/s. (a) 800 Hz–1.5 kHz. (b) 2 kHz–5 kHz. (c) 5 kHz–8 kHz.](image-url)
directivity of the radiated noise also means that this optimum cannot be inferred by a simple linear interpolation of the wire-mesh cell size. The acoustic properties of these liner-type porous treatments with low-resistivity wire-mesh indeed strongly depend on the flow within it, flow penetration which was actually experimentally evidenced for the first time by Yakhina et al.\textsuperscript{38} This was also a conclusion drawn by Teruna et al.\textsuperscript{15} when they simulated the flow within the metallic foam. Finally, at all speeds, the reference configuration also remains the quietest compared to the treated case, which is however a marked difference with the CD airfoil case. This may imply that either the different trailing-edge configuration (different Kutta condition or pressure release) or the strong adverse pressure gradient observed on the CD airfoil or both effects also contribute to flow within the liner-type porous treatment and consequently to the trailing-edge noise reduction.

Conclusions

The present study shows an experimental investigation of the liner-type porous treatments on the trailing edge of a flat plate in the anechoic wind-tunnel of Université de Sherbrooke (UdeS). This class of passive treatments combines rectangular grooves perpendicular to the flow and wire-meshes, and constitutes simplified liners that can be easily implemented on industrial airfoils. The control strategies are threefold: the groove depth is varied (variable groove aspect ratio) and various woven wire-mesh screens with different low porosities and resistivities are placed on top of the grooves. These screens have been selected based on previous tests on a CD airfoil. For the present study, the combinations of three inserts with different cavity depths and three screens with various porosities have been tested. Acoustic far-field and directivity measurements have been carried out at several flow velocities from 15 m/s to 35 m/s for all these configurations. The comparison with the reference flat plate and the flat plate with inserts only is provided as well. For the whole velocity range, measurements have been achieved down to -20 dB, the lowest noise levels that can be reliably in the UdeS open-jet wind tunnel. At low frequencies (below 300 Hz), jet noise was however observed to dominate for all configurations.

The noise from the reference flat plate exhibits the expected trailing-edge noise signature. Moreover, a slight hump observed at high speeds for a Strouhal number based on the plate thickness around 1 suggests an additional edge scattering mechanism caused by the unsteady recirculating area behind the trailing edge. When the cavities are introduced on the trailing edge of the flat plate, an additional noise mechanism occurs at high frequencies characterized by broadband humps and tones: the cavity noise. The SPL at these frequencies rises with the increase of the cavity depth. A coupling between noise generated by the recirculating area after the blunt trailing edge and this cavity noise is also evidenced as previously found on a Katana blade.\textsuperscript{29–31} The former phenomenon is all the higher as the cavity noise increases with the cavity depth. The noise generated by the trailing-edge scattering is shown to follow a dipolar radiation. Yet, two different high-frequency behaviors are found depending on the Reynolds number and the state of the shear layer. Tones are shown to be resonant at the intersection of high order modified Rossiter modes and the cavity depthwise modes as previously evidenced by Block.\textsuperscript{33} As found previously by Howe\textsuperscript{32} for a single rectangular cavity, two different contributions in the cavity noise generated by the transverse groove row can be found, a drag dipole yielding a main upstream directivity lobe and a monopole one that can significantly contribute to a downstream directivity lobe.
When the screens are introduced the noise levels in the mid-frequency range are reduced, and the hump of the recirculating area is damped. The effect of the screens on the cavity noise is much more complex, and may or may not reduce the SPL compared to the plate with inserts alone. On the one hand, screen 1 yields the lowest levels when combined with the shallower insert 3 (actual configuration of the CD airfoil), with levels that are almost systematically below the case with insert alone. On the contrary, screen 2 almost always amplifies the noise generated by the inserts alone, at least in some directions for all flow conditions. Screen 3 shows an intermediate behavior between the other two screens. For all screens, noise is regenerated in the high-frequency range, all the more as velocity (or equivalently the Reynolds number) is increased. This could be traced to the previously observed roughness noise.\textsuperscript{4,12,13} Cavity noise may not be obliterated by the screens and even amplified in some frequency range. A more complex sound directivity is found beyond 5 kHz, with multiple lobes (sign of the plate non-compactness), the amplitude of which strongly depends on the groove depth and type of wire-mesh. Finally, overall the clean flat plate remains the most silent configuration for all tested Reynolds numbers, which is a noticeable difference with the previous CD airfoil experiment.

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