Experimental techniques for measuring sound absorption through micro-perforated partitions

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Abstract
Micro-perforated partitions (MPPs) are robust mid-frequency sound absorbers of practical interest in room acoustics, but also under severe environmental conditions such as in combustion chambers. Experimental characterization of their sound absorption properties is essential to validate the visco-thermal dissipation mechanisms assumed in the models. A number of measurement procedures and test set-ups are presented to estimate the absorption of single- or multi-layer MPPs undergoing acoustic or aerodynamic excitations. In particular, two-sources impedance tube techniques using four microphones enabled sound absorption and transmission measurements through small-sized MPPs under plane wave or multi-modal propagation conditions. Pressure-velocity probe techniques are also described for measuring the sound absorption properties of rigidly-backed MPPs with larger sample size. A dedicated procedure is finally presented to estimate the absorption of boundary layer noise by MPPs flush-mounted in a wind-tunnel test section. The potential and limitations of each of these methods are discussed.

Keywords: absorption, transmission, micro-perforated panels, experimental techniques.

1 Introduction

To overcome the problem of control of low frequency noise avoiding the introduction of active or bulky components, the use of panel with micro-perforations has been considered since a long time. Micro-Perforated Panels (MPP) [1], that can be made of steel, wood or plastic, constitute alternative solutions to porous materials in environments where special hygienic conditions are required, such as food industries or hospitals. Due to the use of MPPs as facing shells, many indoor applications have been developed such as to correct situations with poor intelligibility due to excessive reverberation time [2]. As MPPs can be in contact with a mean flow, they are suitable for natural ventilation in buildings [3] and as acoustic mufflers for HVAC applications [4]. In the field of aeroacoustics, MPPs create minimal flow pressure drop, generating boundary conditions with a very low friction factor, so that the flow generating system does not have to compensate for eventual pressure drop of the MPP wall-treatment to keep a nominal flow rate [5].
It is then of interest to characterize the acoustic properties of MPPs not only in laboratory or controlled environments, but also for different *in-situ* configurations, either when used as rigidly backed partitions, working as Helmholtz resonators, or in unbacked configurations such as room insulators or space sound absorbers. The general objective of the work is to provide examples of different methodologies for the estimation of the sound absorption and transmission through micro-perforated partitions when subject to different pressure fields. The paper is organised as follows: we will start in Sec. 2 by presenting the normalized methods using the impedance tube for incident plane wave acoustic excitation. The methods that

deal with large-size samples under other types of excitations will be explained in Sec. 3, with a procedure based on the use of a pressure-velocity probe. Finally, the characterisation of wall-pressure mufflers excited by a flow-induced excitation will be outlined using a wind-tunnel experimental set-up. The main conclusions and perspectives will be summarised at the end of the work.

2 Impedance tube methods

In this section, we will present the acoustic characterisation of samples that can be adjusted to the dimensions of an impedance tube and excited by a normal incident plane wave. The case of rigidly-backed partition will be analysed first, and then the characterization of two-port systems.

2.1 Absorption measurements on rigidly-backed samples

The most commonly used laboratory-based method for the determination of the absorption coefficient is the two-microphone transfer-function method [6]. The experimental set-up for low frequencies is typically a thick cylindrical tube of length 1000 mm, diameter 100 mm with its first cut-off frequency at 2 kHz. We have used a micro-perforated panel absorber (MPPA) [7] made up of a micro-perforated aluminium disk of radius 50 mm and thickness 0.5 mm, backed by a rigid cylindrical cavity of 45 mm. The circular holes present a diameter equal to the panel thickness and a perforation ratio equal to 0.78%. Figure 1 presents a comparison between the absorption coefficient predicted with an analytical model considering an elastic finite-sized panel [7] and that measured in the impedance tube.

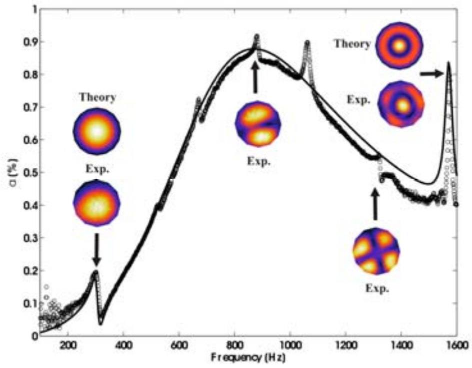


Figure 1- Sound absorption coefficient of the MPPA predicted assuming an elastic (solid black) MPP and measured using the two-microphone method (black circles).

As it can be appreciated, the prediction and the measurements present a reasonable agreement. Measurements show that the absorption performance of thin MPPAs generate extra absorption peaks or dips that cannot be understood assuming a rigid MPPA. To better understand the structural-acoustic interaction between the micro-perforated panel and the backing cavity, the MPP has been backed on the rear face by a thick rigid Plexiglas base (Figure 2), so that the MPP vibrating response can be measured using a Laser Scanning Vibrometer (LSV). The scanning head focussed at 217 points on the disk in order to provide a reliable estimate of the surface average velocity up to 1600 Hz. An optimum laser head – back face stand-off distance of 215 cm – was found to be a good trade-off to keep a low error on the velocity whilst avoiding to detect back-reflections. The vibratory field of the MPP absorber at the panel-cavity resonances identified from the transfer functions spectral peaks are superimposed in Figure 1. The volume-displacing modes (0,0) and (1,0) at their resonance frequencies (298 Hz and 1572 Hz) well agree with those predicted from the vibroacoustic model assuming simply-supported boundary conditions. The MPP absorber is sensitive to the duct acoustic axial resonances which induce maximum air particle velocity at the disk holes, observed at 524 Hz, 671 Hz and 1063 Hz from Kundt's tube measurements. High-order panel-cavity resonances (881 Hz and 1319 Hz) which induce small absorption peaks are also observed [7].

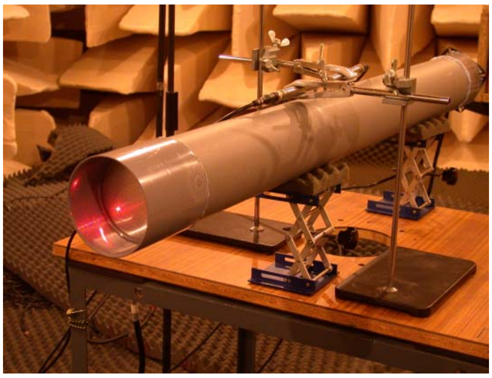


Figure 2- Photograph of the transparent back face of the MPPA for determination of its vibrating response.

2.2 Absorption and transmission measurements

When the partition is not rigidly-backed but transmits sound, its insulation properties can be characterised by the transfer matrix approach [8]. As indicated in Figure 3, an anechoic termination is situated on the transmitting side of the tube and the transfer functions are measured between the loudspeaker drive signal and the sound pressure at two positions upstream of the sample and at two positions downstream of the sample.

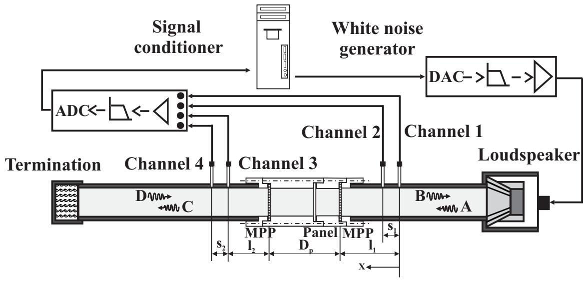


Figure 3- Experimental facility to measure sound absorption and transmission under normal incidence.

The reflexion and transmission coefficients take respectively the expressions

$$R(x = l_1) = \frac{H_{12} - \mathrm{e}^{-\mathrm{j}k_0 s_1}}{\mathrm{e}^{\mathrm{j}k_0 s_1} - H_{12}} \mathrm{e}^{2\mathrm{j}k_0 l_1} , \qquad (1)$$

$$\tau = H_{13} \frac{\mathrm{e}^{\mathrm{j}k_0 s_2} - H_{34}}{\mathrm{e}^{\mathrm{j}k_0 s_1} - H_{12}} \frac{\sin(k_0 s_1)}{\sin(k_0 s_2)} \mathrm{e}^{\mathrm{j}k_0 (l_1 + l_2)} , \qquad (2)$$

with k_0 the acoustic wavenumber, $H_{12} = p_2 / p_1$ the measured transfer function (TF) between the first and second microphones, $H_{34} = p_4 / p_3$ the TF between the third and fourth microphones, and $H_{13} = p_3 / p_1$ the TF between the first and third microphones. s_1 and s_2 are the separation distances between the first and second microphones, and the third and fourth microphones respectively. D_P is the length of the partition. l_1 and l_2 are the distances between the sample and the first and third microphones, as shown in Figure 3. The experimental facility was an in-house set-up made from a 1 cm-thick PVC tube of length 2.70 m. A 9.5 cm inner diameter provides a maximum frequency of analysis slightly less than 2.1 kHz, the first duct cut-on frequency. The two pairs of microphones were separated by a distance of $s_1 = s_2 = \delta = 5\,\mathrm{cm}$. A double layer MPP–MPP–Panel constituted of three panels separated by two cavities has been installed inside the sample holder and a set of experimental measurements has been carried out to evaluate both its absorption and transmission loss (TL) properties [9]. Figure 4 presents the measured results and a comparison with predictions from the transfer approach and a modal formulation.

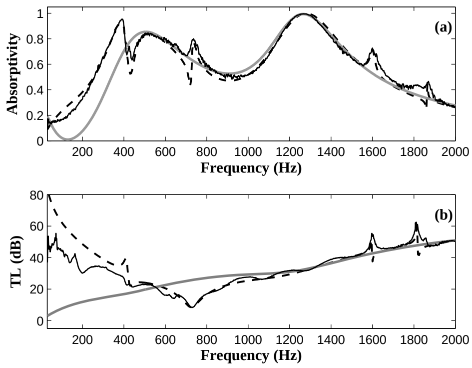


Figure 4 - Measured (black solid) absorptivity (a) and TL (b) for the MPP partition and comparison against predictions by the transfer approach (gray solid) and by a modal formulation (black dashed).

Helmholtz resonances are observed in Figure 4(a) at about 500 Hz and 1260 Hz. As it can be seen, the modal formulation well captures the effect of the structural resonances and correctly describes the observed absorptivity (difference between absorption and transmission) and TL. A reasonable agreement is also found when using the transfer approach above 400 Hz for the absorptivity and above 1.2 kHz for the TL. As expected, the transfer approach underestimates in Fig. 4(b) the sound insulation performance in the low frequency range, by up to about 30 dB below 400 Hz. Such limitations are due to the terminations not being anechoic in the low frequency range. It can however be overcome when considering the use of the scattering matrix $\mathbf{S}$ and the two-source method [10]. The anechoic termination is then substituted by a second source generating a white noise from the radiating side, as it can be seen in Figure 5 (left). The left- and right- sources generate two acoustic states (L) and (R) from which outgoing and ingoing plane wave modal amplitudes are extracted from the transfer functions $H_k^{(s)}$, with $k = 1, 2, 3, 4$ and $s = \mathrm{L}, \mathrm{R}$, between the pressures at the four microphones and the source drive signal. The outgoing modal amplitudes $A_{\mathrm{U}}^{(\mathrm{L}),(\mathrm{R})}$ (resp. $A_{\mathrm{D}}^{(\mathrm{L}),(\mathrm{R})}$) are evaluated on the Up-side (resp. Down-side) of the partition at the microphone 3 (resp. 2) cross-section positions, as follows

$$A_j^{(s)} = -\frac{\mathrm{j}}{2\sin(k_0\delta)}\left(H_{k_j}^{(s)}\mathrm{e}^{\mathrm{j}k_0\delta} - H_{k'_j}^{(s)}\right), \tag{3}$$

while the ingoing modal amplitudes are obtained from

$$B_j^{(s)} = -\frac{\mathrm{j}\mathrm{e}^{-\mathrm{j}k_0\delta}}{2\sin(k_0\delta)}\left(H_{k'_j}^{(s)}\mathrm{e}^{\mathrm{j}k_0\delta} - H_{k_j}^{(s)}\right), \tag{4}$$

with $(k_j, k'_j) = (3, 4)$ if $j = \mathrm{U}$ and $(k_j, k'_j) = (2, 1)$ if $j = \mathrm{D}$. The two pairs of microphones are separated by the same distance $\delta = 5\,\mathrm{cm}$. Matrices of outgoing and ingoing modal amplitudes are built up, leading to a fully-determined problem, $\mathbf{A} = \mathbf{SB}$, of the form

$$\begin{bmatrix} A_{\mathrm{U}}^{(\mathrm{L})} & A_{\mathrm{U}}^{(\mathrm{R})} \\ A_{\mathrm{D}}^{(\mathrm{L})} & A_{\mathrm{D}}^{(\mathrm{R})} \end{bmatrix} = \begin{bmatrix} r^{(\mathrm{L})} & t^{(\mathrm{R,L})} \\ t^{(\mathrm{L,R})} & r^{(\mathrm{R})} \end{bmatrix} \begin{bmatrix} B_{\mathrm{U}}^{(\mathrm{L})} & B_{\mathrm{U}}^{(\mathrm{R})} \\ B_{\mathrm{D}}^{(\mathrm{L})} & B_{\mathrm{D}}^{(\mathrm{R})} \end{bmatrix}, \tag{5}$$

Eq. (5) is readily solved as $\mathbf{S} = \mathbf{AB}^{-1}$, thereby providing the left- and right-absorption coefficients, $\alpha^{(s)} = 1 - \left|r^{(s)}\right|^2$ with $s = \mathrm{L}, \mathrm{R}$, and the left-to-right and right-to-left power transmission coefficients,

$\tau^{(s,s')} = \left|t^{(s,s')}\right|^2$ with $(s,s') = (\mathrm{L},\mathrm{R})$ and (R,L) respectively. Note that $t^{(\mathrm{L,R})} = t^{(\mathrm{R,L})}$ in theory. The measured acoustical properties of a triple MPP–MPP–MPP partition are presented in Figure 5 (right), that exhibit a bandwidth up to 2 kHz. The acoustical performance of the partition is also accurately predicted from an enhance modal matching formulation [11].

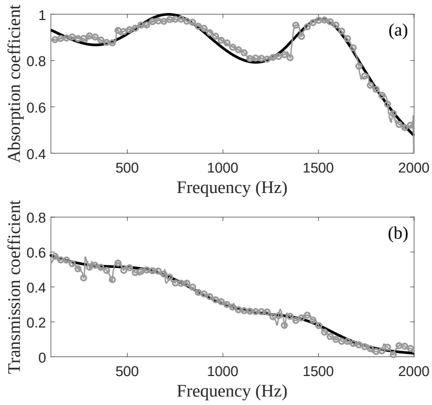
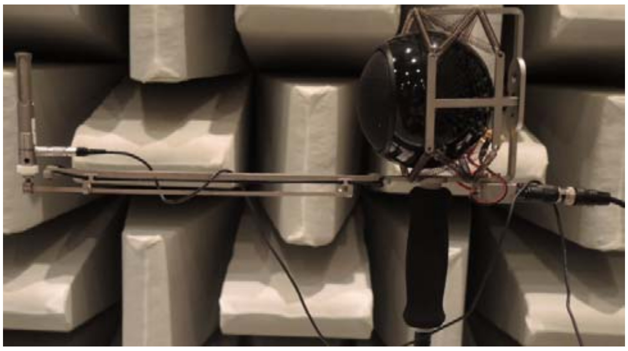


Figure 5 - Photograph of the impedance transmission tube by the two-source method (left) and absorption (a) and transmission (b) coefficients of a multi-layer partition made up of three MPPs under normal incidence: comparison between Kundt tube measurements (gray dotted) and modal approach (black solid).

3 In-situ characterisation methods

In many real-life situations, the determination of the materials acoustic properties using an impedance tube is difficult to carry out. For large-sized samples under general plane wave or spherical acoustic excitation, *in-situ* characterisation methods must be employed that can be based on the estimation of the acoustic velocity by a pressure-velocity probe. In this work, we have used a sensor called Microflown [12] based on the measurement of the temperature difference between closely spaced 200 nm thick platinum wires heated to about 300°C. An incoming pressure field causes a resistance difference measured between the wires. The sensor output voltage then constitutes a good approximation proportional to the acoustic particle velocity across the wires. When considering the case of rigidly-backed partitions, the measurement of their absorption coefficient can be performed using a commercial system denoted as "impedance gun" [12]. It is composed of a collocated *p-v* probe located at a fixed distance to a spherically baffled loudspeaker, as shown in Figure 6 (left).



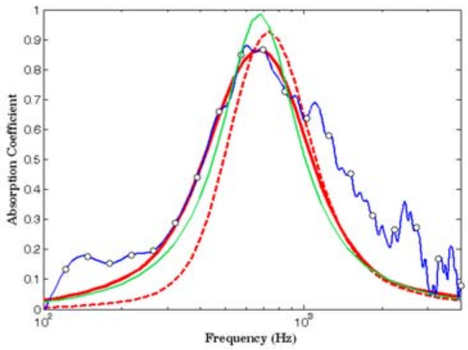


Figure 6 - Photograph of the impedance gun for *in-situ* measurement of the absorption properties (left) and normal incidence absorption coefficient of the input impedance of a fiberglass material shielded by a thin MPP (right): comparison between *p-v* free-field measurements (blue) and predictions from the Miki-Delany-Bazley (green) and from an anisotropic (red-dashed) and fully anisotropic model (solid red) [13].

This probe is used for 1D velocity measurement and contains one particle-velocity and one sound pressure sensor. It allows *in-situ* characterisation of the materials normal absorption and surface impedance properties over a wide frequency range, typically 200 Hz – 15 kHz, and above samples of size $0.5\,\text{m}\times 0.6\,\text{m}$. This *in-situ* measurement system has been used to characterise the absorption coefficient of a rigidly-backed partition composed of 2.4 cm thick cavity filled with fiberglass (fibre radii of $6.5\,\mu\text{m}$ and bulk density equal to $21\,\text{kg}\cdot\text{m}^{-3}$) shielded by an aluminium MPP (1 mm thickness, diameter of the holes equal to 0.5 mm and perforation ratio $\sigma = 0.87\%$) [13]. The measured input impedance is corrected by a free-field calibration factor evaluated prior to the measurements. As a spherical source is used instead of plane wave fields, corrections have to be made for near-field effects and spherical wave front in order to obtain the plane wave impedance. The estimation is made using the mirror source model, that corrects for the elevation of particle velocity in the near field, but not for the spherical wave front. In this method, the reflected sound wave from the surface is represented as a mirror source below the impedance boundary. Other more complicated method, the Q-term model [12], is able to consider spherical geometry of sound fields. In this work, we have avoided errors due to spherical wave propagation within the sample considering a sample thickness lower than 0.04 m and a normal flow resistivity lower than $100\,\text{kNs}\,\text{m}^{-4}$. Also, a short stand-off distance between the probe and the sample, taken as 0.01 m, already limits the amplitude of the side reflections with respect to the direct sound. The results from in-situ measurement of the normal incidence absorption coefficient are shown in Figure 6 (right), with a comparison against analytical models. More information about these predictions can be found in the references [13, 14].
We also faced the case where the *in-situ* partition is a two-port system able to transmit sound through the back side. One considers here an insulating partition composed of two rectangular thin aluminium panels of size $0.42\ \text{m}\times 0.61\ \text{m}$ separated by an air gap of 0.048 m and clamped along their edges on a thick rigid frame. The front side is 0.5 mm thick. It is microperforated with a 0.78 % perforation ratio and with circular holes of 0.5 mm diameter. The whole structure is set in an acoustically rigid stiffened baffle and the front side undergoes plane wave excitation (Figure 7). Two pressure-velocity probes are situated in close proximity to the sample and displaced over a grid of 10×14 evenly spaced locations.

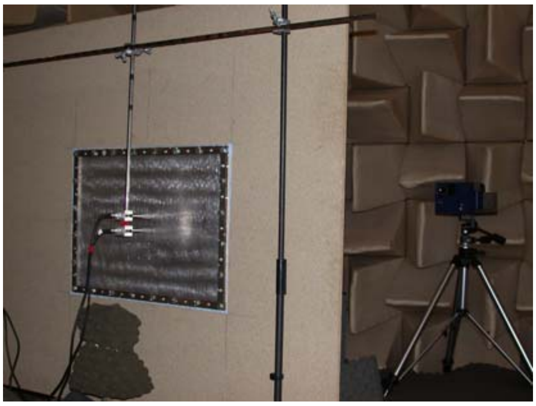


Figure 7 - Experimental set-up for determination of the absorption and transmission properties of the insulating MPP partition, with the laser vibrometer situated in front of the backing side.

The whole system is situated inside an anechoic chamber and an incident plane wave is generated by a far-field baffled loudspeaker located at 0º from the partition axis and driven by white noise. The transmitted sound power is estimated from the back panel velocity measured with a laser vibrometer at 23×32 uniformly distributed positions. Both calculated and experimental values of the absorption coefficient and of the insulating partition are shown in Figure 8. As it can be seen, the experimental results agree reasonably well with the predictions [15].

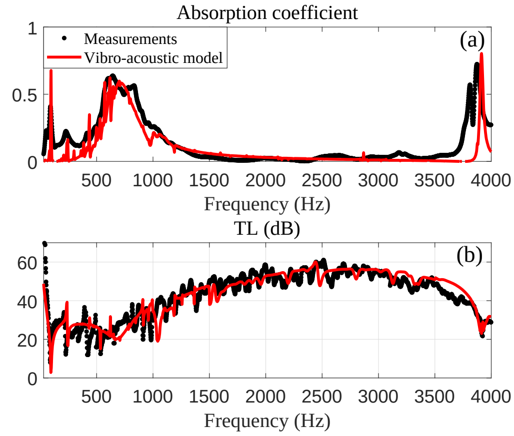


Figure 8 - Absorption coefficient (a) and TL (b) of a clamped micro-perforated partition under normal incidence: modal approach (red solid) and experiment (black solid).

4 Acoustical properties of wall-mounted MPP partitions

Layouts of panels with micro-perforations can be considered for the reduction of the airframe noise radiated outward or transmitted for instance into the cabin of an aircraft. In this section, we want to evaluate experimentally these absorption and transmission properties for a wall-mounted MPP partition backed by a transmitting panel and subject to aerodynamic excitations on the front side. Experiments have been performed in a low-speed wind-tunnel, as indicated in Figure 9. The test section of the closed-loop wind tunnel, situated in the middle, is 7 m long and has a square cross-section of size $0.9\,\mathrm{m}\times 0.9\,\mathrm{m}$. Several silencers are located upstream and downstream the fan section. An even airflow is accelerated through a convergent from a settling chamber equipped with honeycomb straighteners. A sandpaper strip was fixed crossflow on the top wall 2.5 m upstream the test panel in order to efficiently trig the airflow transition to turbulence. Aerodynamic measurements were performed at $U_\infty = 30.7\,\mathrm{m\,s^{-1}}$ with a calibrated DANTEC 55P11 hot-wire probe to measure the mean and fluctuating parts of the flow velocity, showing that a fully-developed turbulent boundary layer (TBL) was established at the partition position.

Figure 9 - Overall view of the low-speed wind-tunnel facility equipped to measure the TL and absorption coefficient of TBL-excited MPP partitions flush-mounted over the top wall of the test section.

Wall-pressure measurements were performed of the point-power and cross-spectral densities between two pinhole microprobes GRAS 40SC (Figure 10), flush-mounted upstream, downstream and over the surface of a MPP for a free-stream velocity $U_\infty = 30.7\ \mathrm{m\,s^{-1}}$. They indicated the spatial homogeneity of the TBL wall-pressures and the absence of flow-excited resonance phenomena over the MPP below 3200 Hz.

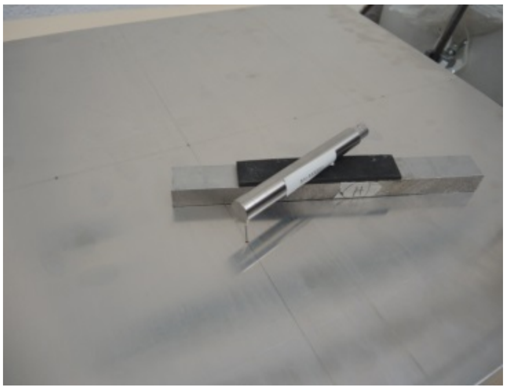


Figure 10 - Photograph of the pinhole microprobe used for the determination of the upper wall wind-tunnel wall-pressure fluctuations under a TBL excitation.

A set of measurements has been carried out in the wind-tunnel test section using a double partition constituted of a MPP front panel, flush-mounted on the test section of the wind tunnel test section and excited by a low-speed TBL of free-stream velocity $30.7\ \mathrm{m\,s^{-1}}$. The MPP is separated by an air gap of thickness $D = 0.03\ \mathrm{m}$ from a plain back-panel that radiates inside an enclosure plugged on the top of the test section (Figure 9), 1.4 m long, 0.5 m wide and 0.8 m high. Both aluminium panels have dimensions of $0.38\ \mathrm{m} \times 0.47\ \mathrm{m}$ along the spanwise and streamwise directions. The front panel is 1 mm thick and microperforated with circular holes of 0.5 mm diameter with a perforation ratio of 0.59% and a holes pitch of 5 mm. The back transmitting panel is also made up of aluminium and has the same thickness than the front panel. The determination of the transmission properties has been performed using a pressure-velocity probe for intensity measurements of the near-field pressure and normal acoustic velocity radiated by the back panel. The TL of the partition is calculated by the expression

$$\mathrm{TL} = 10\log_{10}\left(\frac{S_{\Pi_{\mathrm{inc}}}}{S_{\Pi_{\mathrm{trans}}}}\right), \tag{6}$$

where the spectrum of the incident power is provided by

$$S_{\Pi_{\mathrm{inc}}} = \frac{\Delta s_{\mathrm{MPP}}}{4\rho_0 c_0}\mathrm{Tr}\left[\mathbf{S_{dd}}\right], \tag{7}$$

Δs_{MPP} is the area of the elemental radiators over the MPP, and $\mathbf{S_{dd}} = \mathrm{E}\left[\tilde{\mathbf{d}}_0\tilde{\mathbf{d}}_0^{\mathrm{H}}\right]$ is the Cross-Spectral Density (CSD) of the wall pressure field $\tilde{d}_0$ measured by the micro-probes on the same panel. Figure 11 represents a comparison between the measured results and those predicted by a modal analytical formulation [16].
The absorption coefficient is calculated from

$$\alpha = \frac{S_{\Pi_{\mathrm{diss}}}}{S_{\Pi_{\mathrm{inc}}}}, \tag{8}$$

The dissipated power is composed of two terms [16], the power structurally dissipated by the MPP that is estimated from laser vibrometer measurements performed by transparency through a thick rigid block of Plexiglas flush-mounted in the bottom wall of the test section. The second term represents the power injected through the holes and either dissipated through or radiated by the apertures. This term requires collocated measurement of the pressures on the external and cavity sides of the MPP, that could not be achieved in the experiment, so this second term was approximated by the trace of $\mathbf{S}_{\mathbf{dd}}$ obtained from microprobe measurements over the MPP external side. This explains the differences between the measurements and predictions (solid and dashed red lines) in Figure 12. For comparison we also present the results with a plain front panel.

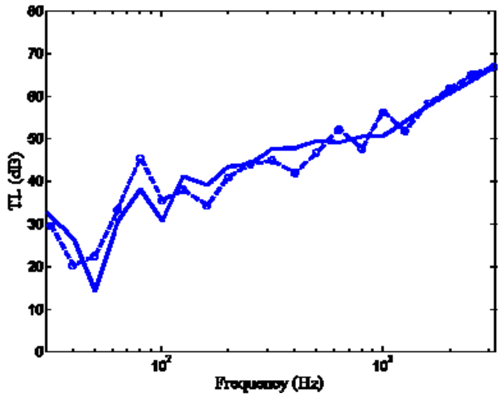


Figure 11 - Third-octave averaged TL curves for the micro-perforated partition under a TBL excitation: measured (blue dashed) and predicted (blue solid).

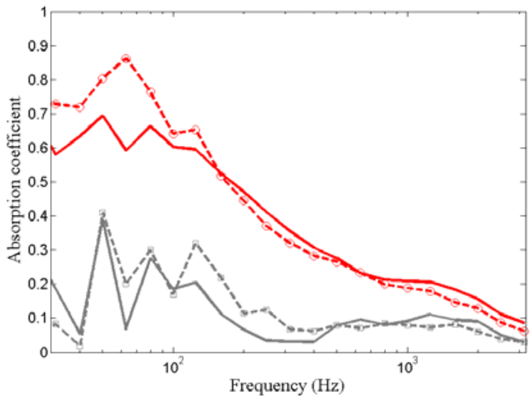


Figure 12 - Third-octave averaged absorption curves for a number of partitions undergoing a TBL excitation: plain front panel (solid grey: calculated; dashed grey: measured), micro-perforated front panel (solid red: calculated; dashed red: measured).

5 Conclusions

Micro-Perforated Panels are suitable noise-reducing solutions in demanding environments. This work has presented several methods for the characterization of their acoustic performance when excited by different pressure fields. The normalized impedance tube methods can be applied to small samples excited by a normal plane wave. When they are rigidly-backed, the two-microphone method is the most widely used laboratory-based determination method. If the MPP partition is able to transmit power, the transfer matrix method using four microphones and an anechoic termination on the radiating side can be used taking into consideration the limitations in the low frequency range. Otherwise, the scattering matrix method can properly characterize absorption and insulation properties of MPP partitions. For larger samples under normal or oblique excitations, *in-situ* characterization methods using an acoustic probe have been developed based on the measurement of the pressure and normal particle velocity nearby the MPP front side. Finally, we have characterized wall-mounted MPP partitions used as silencers in flow duct acoustics, presenting also a procedure to determine their aero-acoustical performance in presence of an acoustic and/or turbulent excitation.

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