ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Architectural Acoustics
Session 2aAAb: New Materials for Architectural Acoustics

2aAAb6. Analysis of sound absorption behaviour of polyester fibre material faced with perforated panels
Davide Borelli, Corrado Schenone* and Ilaria Pittaluga

*Corresponding author's address: DIME, University of Genova, Via all'Opera Pia 15/A, Genova, 16145, GE, Italy,
corrado.schenone@unige.it

Perforated facings used in lined ducts or sound absorbing panels can have various purposes: protecting the porous sound absorbing material from dust or grazing flow, acting as a rigid support for the porous material, or also affecting the behaviour of the “backing” material, modifying this way the acoustical performance of the porous layer. This paper describes the effect of perforated facings on sound absorption characteristics of samples made by polyester fibre, experimentally investigated in accordance with ASTM C384 04 standard by means of two Kundt's tubes with different diameters. The polyester (PET) fibre material had bulk density of 30 kg/m$^3$ and melting point at 260°C. The analysis was performed for a sample thickness equal to 100 mm. The samples were faced by means of different metal plates perforated with circular holes. The holes diameter was equal to 2 mm for all facings, while the percent open area was varied from 4.9% to 30%. The perforated panels were positioned in adherence of the PET fibre material or at a distance of 2, 4, and 6 mm. The different behaviours due to the multiple combinations of percent open area and distance from the sample have been then analyzed and discussed.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

Perforated facings used in lined ducts or sound absorbing panels can have various purposes: protecting the porous sound absorbing material from dust or grazing flow, acting as a rigid support for the porous material, or also affecting the behavior of the “backing” material, modifying this way the acoustical performance of the porous layer.

In spite of that, while the acoustic characteristics of perforations in contact with air alone have been extensively investigated, literature on perforations facing sound absorbing material is currently not so plenty. Ingard [1] theoretically analyzed the effect of perforation and of air gap between the facing and the absorbing material and concluded that the air gap between the perforation and facing material narrows the effective frequency range of absorption coefficient. Twenty years later, Davern [2] studied the effect of porosity and wall thickness of the perforated facing, measuring the perforated facing impedance in the absence of the fibrous material and empirically adding the acoustic properties of the material to consider their effect. Munjal e Thawani [3] theoretically analyzed the effect of the percent open area of a perforated panel facing a highly porous fibrous material. Kirby and Cummings [4] proposed a semi-empirical correlation to calculate the impedance of the perforation when backed by absorbing material in the presence of a grazing mean flow. A wide review of such a topic is reported in [5], where a detailed analysis of the subject is presented, from both theoretical and experimental point of view. A further research was implemented successively by Lee et al. [6], who experimentally analyzed the acoustic impedance of perforations in contact with fibrous materials, varying porosity and holes diameter of the facing, together with the density of the fibrous material. Allard and Atalla dedicated a paragraph of their book [7] to the modeling of porous material with perforated facing, summarizing the state of the art. More recently, Borelli and Schenone [8] studied the effect of perforated facing on sound absorption of polyester fibre material.

In the present paper, the effect of perforated facings on sound absorption characteristics of samples made by polyester fibre has been experimentally investigated in the frequency range 160 - 2500 Hz. Experiments have been performed on the basis of ASTM C384-04 standard [9] by means of two Kundt’s tubes with different diameters. The different behaviors due to the multiple combinations of percent open area and to the air gap from the absorbing material have been then analyzed and discussed.

EXPERIMENTAL SET-UPS AND PROCEDURE

Sound absorption coefficients and surface impedances were measured applying the Standing Wave Ratio method by means of two cylindrical Kundt’s tubes of different diameters, both made of transparent PMMA. The use of two tubes permitted to widen the frequency range for which the study has been performed, as described below.

The first one is a vertical standing wave tube with a 0.19 m inner diameter and 2 m total length, compliant with ASTM C384 04 standard (Fig. 1). The sound source consists of a loudspeaker 200 mm in diameter, placed at the top of the tube. The bottom of the tube is made of a metal disk with a thickness of 40 mm which acts as the rigid reflection surface. The microphone and its preamplifier are suspended inside the tube through the microphone cable. Acting on the cable the microphone can translate along the entire length of the tube. The loudspeaker is powered by a sinusoidal signal. The measurement system also includes a sound level meter analyzer, which allows frequency analysis in octave bands and third octave band, an oscilloscope and a digital multimeter, used for the analysis of output voltage. To apply the Standing Wave Ratio method is necessary that at least a minimum and a maximum of the pressure magnitude can be measured inside the tube. Therefore, a length of the tube greater than $\lambda/2$ (where $\lambda$ is the wavelength of the lowest frequency which is investigated) is needed. This condition imposes a lower limit to the frequency of measurement corresponding to 142 Hz because of the minimum useful length of 1.81 m. Frequency upper limit is imposed by the need to have a plane wave inside the tube. Applying Rayleigh theory [10] the highest frequency that can be investigated is equal to 1058 Hz because of the diameter equal to 0.19 m.

The second experimental set up, with an inner diameter of 70 mm and an effective length of 630 mm, has an horizontal axis and a movable test section (Fig. 2). One 1/2" microphone is fitted in through a hole, suitably lined by soundproofing material to make the test section acoustically sealed. A metallic disc 40 mm thick and 70 mm wide has been used like bracket for the absorbing samples at one end of the tube, while a loudspeaker with the same diameter operates like sound source at the other end. The bracket and the loudspeaker can be separately moved along the tube by means of rods and so realize a test section with a variable length. The sliding rods, besides regulating the relative position between the sound source and the sample, are connected by an external rod, which allows the loudspeaker and the sample to be solidly moved. In this way, by means of a fixed microphone, maximum
and minimum pressure values along the tube can be detected. This experimental set up allows a larger flexibility in comparison with the strict application of ASTM C384-95 standard, which according to the rule requires the sound absorption coefficient to be calculated by a tube with a fixed length, depending on the minimum frequency of interest, and with a mobile sliding microphone to measure the Standing Wave Ratio. To include the effects of attenuation in the calculation two minimums were used, so that the lower frequency of the range is given by 408 Hz. The upper limit of the usable frequency is imposed by the need for plane waves in the tube. According to Rayleigh theory, this condition is verified up to frequencies for which wavelengths are greater than 1.707 times the diameter of the tube; for this set up to 2871 Hz. The accuracy of the set-up was tested by comparing results measured for a similar sample of polyurethane at open cells from the present set up with those ones obtained during an interlaboratory Round Robin Test [11]. The comparison between the experimental data from the current apparatus and the maximum deviation obtained by the eleven laboratories involved in the above mentioned RRT, showed that measured values fall within the confidence limits of the test, so indicating a satisfactory accuracy [12]. Experiments were performed on polyester (PET) fibre samples with bulk density of 30 kg/m$^3$ and melting point at 260°C. The study considered a samples’ thickness equal to 100 mm. The samples were faced by means of different metal plates perforated with circular holes. The holes diameter was equal to 2 mm for all facings, while the percent open area was varied from 4.9% to 30%. In Figure 3 a sketch of the different metal plates used as perforated facing for the horizontal and vertical Kundt’s tube is shown. The perforated panels were positioned in adherence of the PET fibre material or at a distance of 2, 4, and 6 mm.
The acoustical behavior of unfaced polyester fibre samples was firstly characterized by measuring flow resistivity, \( R_1 \), and sound absorption coefficient at normal incidence, \( \alpha \), by means of the standing wave ratio (SWR) method. Flow resistivity was measured according to ISO 9053:1991 standard [13], direct airflow method (method A), and resulted to be equal to 4285 Pa-s/m², that is a typical value for this material and density.

Experimental data were compared with literature correlations from Delany-Bazley [14], Dunn-Davern [15] and Garai-Pompoli [16], which is especially intended for polyester fibre material (Fig. 4). The comparison showed a good agreement between measured and calculated values; in this way the accuracy of the experimental set-ups and of the operating procedure was further validated.

**FACING WITH PERFORATED PLATES: EFFECT OF THE PERCENT OPEN AREA**

To analyze the effect of perforations on the acoustic behavior of absorbing material the samples were faced by means of different metal plates perforated with circular holes. During all experiments metal plates were 1 mm thick. The holes diameter was equal to 2 mm for all facings but the percent open area, \( \sigma \), was varied from 4.9% to 30%.

The percent open area for each perforated facing is defined as:

\[
\sigma = \frac{\text{perforated area}}{\text{total area}} \times 100 \%
\]  

(1)
First, metal plates were put in close contact with the polyester fibre material. Normal incidence sound absorption and acoustic impedance were measured for all facings.

In Fig. 5a the sound absorption coefficient curves in one-third octave band for the samples faced with the different perforated facings are shown in comparison with the unfaced sample. The diagram indicates that, in general, when the open area increases, the curves for faced and unfaced samples tend to be closer, that is the effect of facing reduces meanwhile the open area increases. In particular, when the percent open area is equal to 30%, for both in relation to the acoustic impedance (Fig. 5b), the real part does not depend on the open area and the imaginary part tends to increase when the percent open area reduces, due to the added mass to the facing; this effect decreases as the percent open area increases, to become negligible when it is equal or greater than 20%. This behavior exactly corresponds with what models predict for this facing thickness and smaller holes’ diameter: the real part does not markedly increases until the open area is greater than 2.5%, while the imaginary part presents values increasing with the frequency and the open area.

Present experimental data essentially agree with literature results. Munjal and Thawani [3], at the end of their theoretical analysis, conclude that for highly porous fibrous material a thin perforated of 34.9% percent open area is practically as good as 100% percent open area whereas a 4.9% percent open area affects absorbing behavior at high frequencies, and suggest that about a 10% percent open area is a good design compromise between acoustical performance and mechanical strength. Similarly in Ingard [1], where the effect of a perforated panel with a percent open area of 7.7% is theoretically analyzed and a considerable effect on absorption coefficient curves of porous materials is predicted.

Those conclusions are substantially confirmed by the present study, i.e. protective layers may have a dual function, which is to work like a mere support to the porous sound-absorbing material or to operate like a real absorbent panel according to the open area. The different intended use therefore depends on the percentage of perforation: in the event that it is equal to or greater than 20% of the surface of the facing [17], this assumes the only function of supporting and protecting the sound-absorbing material.
FIGURE 6. Air gap $d$ between the perforated facing and the absorbing material (vertical Kundt’s tube): $d=2$, 4 and 6 mm.

FACING WITH PERFORATED PLATES: EFFECT OF THE AIR GAP BETWEEN THE FACING AND THE ABSORBING MATERIAL

The effect of the gap between the perforated facing and the absorbing material was then analyzed for the diverse $\sigma$ values considered in the experiments previously described. The perforated facing distorts the sound field in a small area around the holes, for a distance from the facing of only about one perforation diameter [1]. When the

FIGURE 7. Absorption coefficient curves for diverse air gap $d$ between the perforation and the absorbing material: a) $\sigma = 4.9\%$; b) $\sigma = 7.7\%$; c) $\sigma = 10\%$; d) $\sigma = 15\%$; e) $\sigma = 20\%$; f) $\sigma = 30\%$. 
FIGURE 8. Normalized acoustic impedance curves for diverse air gap \( d \) between the perforation and the absorbing material: 

a) \( \sigma = 4.9\% \); b) \( \sigma = 7.7\% \); c) \( \sigma = 10 \% \); d) \( \sigma = 15\% \); e) \( \sigma = 20\% \); f) \( \sigma = 30\% \).

facing is so close to the porous material that the distorted part falls inside the material, the facing creates not only an inertial effect but also a resistive effect. In this way, the surface acoustic impedance of the perforation facing the absorbing material is influenced by the air gap existing between the facing and the material. When the air gap is sufficiently wide the effect of the perforated facing is only a mass reactance which adds the impedance of the porous layer; else, the facing acts as a resistance as well and the normal impedance of the faced porous material is influenced. The impedance of the porous material covered by a perforated facing therefore depends on the dimension of the air gap, since the real part of the impedance depends on the flow resistivity of the material in contact with the facing.

To the aim to experimentally analyze such an effect, three different air gaps of 2, 4 and 6 mm were obtained between the perforated facing and the material (Fig. 6). These gaps respectively correspond to 1, 2 and 3 diameters of
perforation’s holes. Experiments were performed for all the diverse \( \sigma \) values and both sound absorption coefficient (Fig. 7), both surface impedance (Fig. 8) were measured in the range from 160 to 1000 Hz by means of the vertical Kundt’s tube.

Air gaps seem to affect only slightly the acoustic behavior of the covered absorbing material. Differences among \( \alpha \) curve for the diverse air gaps result to be very small for all tested percent open areas. In particular, when the dependence of the acoustic impedance on air gap is examined, no evident effect is observed for all \( d \) values considered during the experiments. This result appears to be valid for all values of percent open area and for real and imaginary part.

These results are not in conflict with the model proposed by Allard and Atalla [7] for porous material with perforated facings for the case of circular holes, which predicts a certain shift in \( \alpha \) curves, but of minor entity. Since in the present case the flow resistance \( r_d/pc \) of the porous material is equal to 1.2, Ingard model [1] would presume a stronger effect of the air gap on sound absorption coefficients of the faced absorbing material, which has not been actually observed during the experiments. On the contrary, unlike \( \alpha \), changes in \( d \) values did not influence impedance or absorption coefficient.

It must be underlined that whereas the percent open area, as well as holes’ diameter and facing thickness, can be exactly fixed by the manufacturing, the air gap between the perforated plate and the fibrous material is really difficult to control, since the surface of the absorbing sample is not smooth, but present undulations with a magnitude close to the nominal air gap. This problem cannot be overcome if not by adopting in the experiments not fibrous porous material; nevertheless, in the most part of technical situations exactly this kind of sound absorbing material is actually utilized (dissipative silencers, sound absorbing panels, acoustical barrier, etc.), so that this issue cannot be ignored.

CONCLUSIONS

In this study the effect of perforated facings on acoustic characteristics of a sound absorbing material has been experimentally investigated. The different behaviors due to the multiple combinations of percent open area and air gap from the sample have been then analyzed and discussed.

To analyze the effect of perforations, polyester fibre samples were faced by means of different metal plates perforated with circular holes (\( \Omega = 2\text{mm} \)), at first put in close contact with the absorbing material. Experimental data essentially agree with literature results, i.e. the acoustic properties result to depend on the percentage of perforation: in the event that it is equal to or greater than 20% of the surface of the facing, this assumes the only function of supporting and protecting the sound-absorbing material. For lower percent open area, as \( \sigma \) decreases, the \( \alpha \) curves for faced and unfaced samples tend to distance, thus indicating a different acoustical behavior of the lined duct or of the absorbing panel on which the facing is applied. In particular, the frequency corresponding to the peak value of \( \alpha \) tends to decrease, just as the theoretical models foresee. The real part of the impedance very slightly depends on \( \sigma \), while the imaginary part increases when the percent area ratio reduces, due to the added mass to the facing.

 Afterwards, the perforated plates were positioned at a distance of 2, 4, and 6 mm from the absorbing material, measuring the variation of the sound absorption coefficient with the air gap. Air gaps seem to affect only slightly the acoustic behavior of the covered absorbing material. Differences among \( \alpha \) curve for the diverse air gaps result to be very small for all tested percent open areas. In particular, when the dependence of the acoustic impedance on air gap is examined, no evident effect is observed for all \( d \) values considered during the experiments. This result appears to be valid for all values of percent open area and for real and imaginary part.

In general, experiments confirmed the acoustic behaviour of the faced absorbing material deeply depends, among other issues like holes geometry, wall thickness and medium in contact with the facing, on the perforated percent area and, somehow, on the air gap facing-material. Such a variation of sound absorption coefficients and specific surface impedances can greatly influence the performance of the dissipative silencers, thus asking for a better comprehension and an accurate modelling of the physical phenomenon.

ACKNOWLEDGMENTS

The authors would like to thank Prof. Ruggero Bartolini for his support and assistance.
REFERENCES