In situ characterization of wall linings with perforated facings

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ABSTRACT

The in-situ characterization of acoustic materials is one of the main challenges in room acoustics. Previously, the characterization of a single porous layer backed by a hard wall was successfully done by combining pressure-velocity measurements near the surface of the material with an impedance model fitting approach. In practice however, many porous materials are mounted behind a membrane or a rigid perforated facing.

By again combining pressure-velocity measurements and a model fitting procedure, this work studies the possibility to characterize such systems. This was done by measuring a variety of perforated facings and membrane facings, whether in front of an air cavity or backed by a porous layer and comparing the obtained impedance model parameters to the reference values. Good agreement was observed between the retrieved parameters and the references, with error in retrieved moving mass, facing thickness, cavity depth, porous layer thickness and porous layer flow resistivity not exceeding 15%.

1. INTRODUCTION

The acoustic characterization of materials is one of the challenges in room acoustics, as the properties of the materials laid out can have a significant impact on the acoustics of a given indoor space. It is in some cases crucial to measure the material in situ, because the mounting conditions and the wear of time can alter the material properties compared to measurements in the laboratory. Moreover, in situ measured data may be valuable in the context of the implementation a room acoustic simulation of an existing space, as it avoids the problem of bringing the material to the laboratory for a standardized impedance tube measurement [1].

In a previous work by the authors, an in situ characterization method was introduced [2]. This method combines a pressure-velocity (PU) measurement for a sound wave with normal incidence to the surface to characterize with an impedance model fitting procedure. It was shown that this approach allowed an accurate characterization of hard-backed porous layers.

However, in most applications, the surface of the acoustic materials installed in a room are not left bare. Their visible surface is usually covered for sustainability and aesthetic purposes. While these facings can have a negligible effect on the acoustics, they are in some cases designed to be an integral

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part of the acoustic system, usually adding a resonant sound absorption mechanism to the porous absorption. One of the most typical types of acoustic covering is a perforated wooden plate [3].
The goal of this study is to evaluate the applicability of the in situ characterization method for multi-layered acoustic systems that feature a rigid perforated facing. To this intent, a variety of combinations of perforated panels with two backings (a 45 mm air cavity and a porous layer) were measured experimentally and the results of the inverse characterization were compared to reference values.
This paper is structured as follows: The method used to characterize the system in situ is presented in Section 2 and introduces the impedance models used for the fittings. In Section 3 the measurement campaign realized to verify the validity of the approach is described, with the results presented and discussed in Section 4. Finally, the conclusions of this work are given in Section 5.

2. METHODS

The in situ characterization method proposed in this work follows the same general layout as the procedure described in Ref. [2]. It consists of two steps: a PU *in situ* measurement above the surface of the boundary system to characterize, and a post-processing that retrieves the non-acoustical parameters of the system based on a model-fitting procedure.

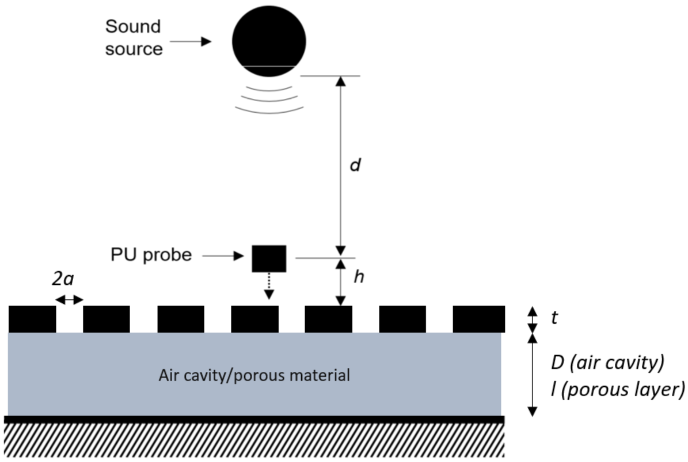

Figure 1 – Arrangement of sound source and PU probe above the perforated facing system to characterize.

2.1. Impulse response measurements

Impulse responses of the acoustic pressure and normal particle velocity are captured with a PU probe near the material's surface ($h < 20$ mm), as well as in free field, with a small sound source in vertical alignment with the probe at a distance $d = 260$ mm. The configuration used to measure the material's surface is pictured in Figure 1. After a time-windowing step with the Adrienne window [4] that allows the removal of late parasitic reflections, the impedance in free field Z_{ff} and near the material surface Z_m are computed from the measured impulse responses and the normal reflection coefficient is estimated as [5]

$$R_{in\ situ}(h) = \frac{\frac{Z_m}{Z_{ff}} - 1}{\frac{Z_m}{Z_{ff}}\left(\frac{d}{d+2h}\right)\left(\frac{ik(d+2h)+1}{ikd+1}\right)+1} e^{ik2h}. \quad (1)$$

Equation (1) estimates the reflection coefficient under the assumption that both incident and reflected wave are plane waves but includes a correction for the amplitude decay of spherical propagation, which provides more accurate results for a short source-to-probe distance.

2.2. Model fitting procedure

The way chosen to model the perforated facings was the one introduced by Atalla and Sgard. It models the perforated facing with an equivalent propagation constant and characteristic impedance, based on the Johnson-Champoux-Allard (JCA) theory [6]. In this framework, the parameters of the equivalent JCA fluid (resistivity σ, porosity φ, tortuosity α_∞viscous length Λ and thermal length Λ') are derived from the geometry of the facing: the perforation radius a, the open ratio ε and the tube length t. For a facing with circular perforations, the equivalent JCA parameters are estimated from:

$$\varphi_{eq} = \varepsilon \tag{2}$$

$$\Lambda_{eq} = \Lambda'_{eq} = a \tag{3}$$

$$\sigma_{eq} = \frac{8\eta}{\varepsilon a^2} \tag{4}$$

$$\alpha_{\infty,eq} = 1 + \frac{2\delta a}{t}, \tag{5}$$

with η the dynamic viscosity of the air. Following these relations the characteristic impedance $Z_{JCA,eq}$ and propagation constant $k_{JCA,eq}$ of the equivalent fluid are calculated through the JCA model formulations, for example presented in Ref. [7].

This model of a facing depends on the perforation radius a and open ratio ε of the perforated facing, which are straightforward to evaluate by direct geometrical measurement of the system's surface, and the facing's thickness (or tube length) t. This latter parameter remains the only parameter to retrieve to characterize the perforated facing, because it is generally not possible to directly measure it without taking off the facing.

In this work however, an additional generic resistance r_c is added to the surface impedance of the system to account for the fact that the material from which perforated facing is made (in this case MDF) is not perfectly reflective and thus induces additional losses. The parameters to retrieve to characterize the facing are thus (t, r_c).

From these considerations the surface impedance of the system is computed with a regular transfer matrix calculation:

$$Z_s = r_c + \frac{-jZ_b Z_{JCA,eq}\cot(k_{JCA,eq}t) + Z_{JCA,eq}^2}{Z_b - jZ_{JCA,eq}\cot(k_{JCA,eq}t)}, \tag{6}$$

where Z_b is the surface impedance immediately behind the facing. In this work, its expression is either $Z_{b,cav} = -j\rho_0 c_0 \cot(k_0 D)$ for the air cavity backing or $Z_{b,por} = -jZ_p \cot(k_p l)$ in the case of a porous layer backing, where the porous layer's characteristic impedance and propagation constant are extracted with the formulation of the Delany-Bazley-Miki model [8]. From these expressions the modeled reflection coefficient is

$$R_{model} = \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}, \tag{7}$$

and the cost function used to fit the measured data is

$$F = \sum_{\Delta f} \| Re(R_{in\,situ} - R_{model}) \| + \| Im(R_{in\,situ} - R_{model}) \| \tag{8}$$

with Δf being the frequency range of the fitting, which in this work is [500, 10000] Hz. For the fittings performed in this work, the elements of the frequency vectors were logarithmically spaced to avoid a larger weight of the higher frequencies.
The cost function F is minimized in MATLAB with the *fmincon* function used as core solver to a *MultiStart* object, which runs the solver for a given number of starting points uniformly distributed across the search space, and yields the best minimum. The search space is defined by the upper and lower search boundaries for each parameter, which can be found in Table 1.

Table 1: Lower (x_l) and upper (x_u) of the search space for the optimization variables in this study

	x_l	x_u
t [mm]	0	10
r_c [Pa s/m]	0	1e4
σ [kPa s/m2]	1	1e3
l [mm]	0	200
D [mm]	0	200

3. IN SITU MEASUREMENTS

A measurement campaign was conducted to characterize a set of systems featuring perforated facings. The three perforated perforated facings investigated were made of 16 mm thick Medium Density Fiberboard (MDF) and featured straight circular perforations in square patterns, with varying perforation radii: 5 mm (Perf I), 4 mm (Perf II) and 3 mm (Perf III). The lateral dimensions of the sample were 0.6 m × 0.6 m. Each of the panels was coupled with two rigidly backed conditions:

- a 45 mm air cavity, which was created by putting the facing on top of rubbers bars;
- a 40 mm glass wool layer (flow resistivity 30 kPa s/m2);

This led to a total of 6 acoustic systems to characterize. The measurements took place in the workshop space of the Echo building at the Eindhoven University of Technology. The room was not empty, as measurement equipment and various objects were present, but a clearance radius of around 1.5 m around the measurement location was arranged. The systems to characterize were mounted directly on the floor of the room made of a 300 mm thick smooth concrete slab, which served as rigid backing. The measurements were realised with the "*In situ* absorption testing" (name by the manufacturer, Microflown Technologies). It consists of a PU probe attached to a small round loudspeaker via a light decoupling structure, which sets the source-to-probe distance to 260 mm.
The source signal, a 5 seconds e-sweep sine, was produced from a laptop running the room acoustic software DIRAC 6. The signal was sent to an amplifier before being sent to the small source. The acquired signals were recorded by the same laptop and the de-convolutions into impulse responses were performed by DIRAC 6. The setup was positioned close to the panel's surface with the help of a tripod, so that the probe was located at a height h_{ref} = 10 mm above the surface and the source vertically aligned with the probe, as shown in Figure 2. The velocity sensor was carefully oriented to capture the velocity normal to the sample's surface.
As for the horizontal location above the plane, the PU probe was placed within the confidence region for PU probe measurements, which minimizes the influence of the sound waves diffracted on the

edges of the samples [10]. This means that the probe was placed within a distance of $L/3$ from the center of the sample, with L being the side length of the sample. Additionally, care was taken to not place the probe exactly at the centre of the sample, where edge-diffracted waves interfere constructively. The distance from the source and receiver to the first reflective surface of the measurement environment was measured around 1.5 m. The approximate time delay between the incident sound peak and the first parasitic reflections is thus computed as Δt_{refl} = 7.4 ms, and was then used as time-window length.

Figure 2 – Placement of the PU probe above one of the systems characterized (perforated facing II backed with porous material).

4. RESULTS AND DISCUSSION

In Table 2, it is seen that the values of the cavity depth and facing thicknesses are retrieved with very good accuracy, with maximum errors of 4% and 6% respectively. These errors could be due to a small misalignment of the rubber bars used to create the cavity. It can also be seen that the generic resistance retrieved is increasing with decreased perforation radius. Additionally, and this can be observed throughout all the result tables presented in this Section, it can be observed that the values retrieved for the probe-to-sample distance h hover within the range from 8 to 13 mm, which is less than 3 mm away from the value targeted for the measurements (10 mm).

It can also be seen that the error values for the case of a porous layer backing are very low. The error for the facing thickness was always less than 0.5 mm away from the reference value, which results in a relative error of 0% after the value is rounded to the millimeter. As for the retrieved values for the flow resistivities and the thicknesses of the porous layers, it can be observed that the relative error values are below 8%, and 5% respectively. It can be seen that similarly to the case of the air cavity, the retrieved resistance increases when the radius of perforation decreases. The retrieved resistance values are however lowered by an offset of around 150-250 Pa s/m2. This offset value can thus be seen as the losses within the 45 mm air cavity (which is now filled with a porous layer), while the remaining losses are accounting for the losses in the perforations that are due to the porosity of the MDF, which are not accounted for in the model.

Table 2: Characterization results of the measured systems

		Perf I	Perf II	Perf III
Air cavity	t^* [mm]	17	16	16
	r^* [Pa s/m]	210	302	342
	D^* [mm]	46	47	46
	h^* [mm]	11	8	8
Porous material	t^* [mm]	16	16	16
	r^* [mm]	0	60	143
	σ^* [kPa	31	30	28
	l^* [mm]	39	40	39
	h^* [mm]	9	9	10

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The curve fittings in the air cavity case are shown in Figure 3, the ones in the porous layer backing case in Figure 4. Comparing these two Figures, it is visible that the replacement of the air cavity by a porous layer changes greatly the resulting reflection coefficient. Two main differences can be observed: Firstly, the multiple sharp cavity resonances above 3 kHz have disappeared with the introduction of a porous layer, as the layers prevent the formation of modes in the cavity. Moreover, it is observed that the sharpness (or quality factor) of the Helmholtz resonance (lowest lobes on the plots) is decreased in the porous layer configuration because of the additional damping brought by the layer. It can be observed that in both case the measurements and the models match well from 500 Hz to 10 kHz, but deviate below 500 Hz outside of the fitting frequency range. This is because the measurement procedure made use of a plane wave propagation above the system (Equation 1), which is untrue in these lower frequencies for the source-to-sample distance used (260 mm).

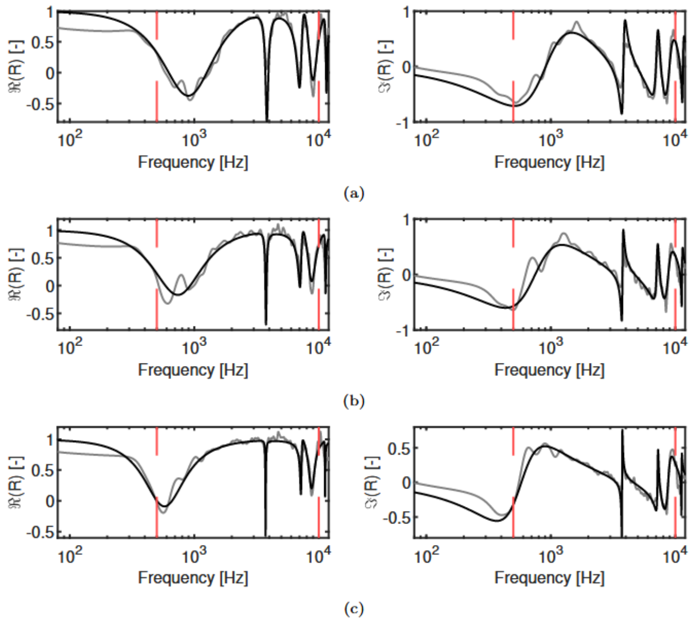

Figure 3 – Measured and model fitted complex reflection coefficient of (a) Perf. I, (b) Perf. II and (c) Perf. III backed with the 45 mm air cavity, using the equivalent JCA model for the facing. Grey line: $R_{insitu,\ opt}$; Black line: $R_{model,\ opt}$ Red dashed lines: limits of model fitting frequency range.

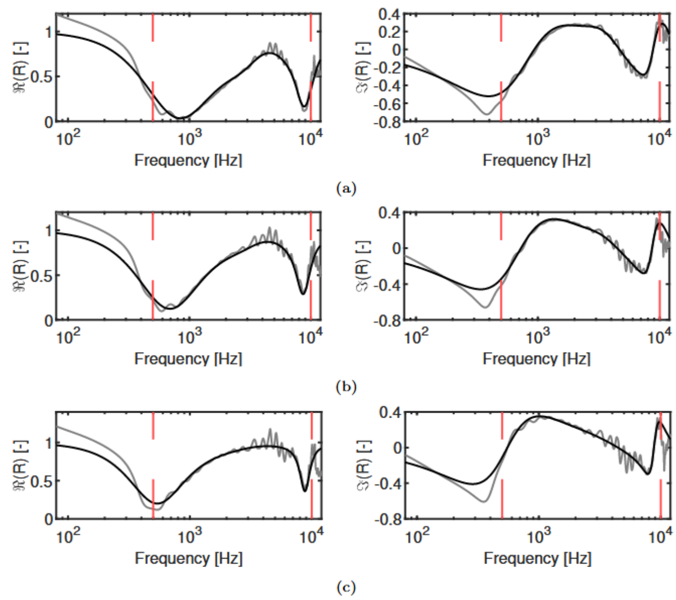

Figure 4 – Measured and model fitted complex reflection coefficient of (a) Perf. I, (b) Perf. II and (c) Perf. III backed with Material A, using the equivalent JCA model for the facing. Grey line: $R_{insitu,\ opt}$; Black line: $R_{model,\ opt}$ Red dashed lines: limits of model fitting frequency range.

5. CONCLUSIONS

In this work, the in situ characterization of perforated panels backed by an air cavity and porous layers was experimentally investigated with a method combining a PU based in situ measurement and a

model fitting procedure. The equivalent JCA model was the model used to model the perforated facings.
The JCA-equivalent model of the perforations allowed a good curve fitting of the measurement data up to 10 kHz. It also retrieved with excellent accuracy the thickness of the facing and the properties of the backing layers (porous layer or air cavity). The generic resistance term retrieved was non zero in most cases, showing that besides the losses in the air cavity, not all of the losses in the facing were predicted by the equivalent JCA model, most likely because the material of the facing is not perfectly rigid and smooth.
The work realized in this chapter calls for several future works. The first of them could be to test the applicability of the characterization procedure to a greater variety of perforated facings, with various perforations shapes and patterns, as well as slotted and grooved panels. Another interesting type of facing to investigate are the micro-perforated panels. The applicability to more complex systems, such as a *facing + porous layer + air cavity* system, is also of interest.
Finally, many perforated facings (but not the ones measured in this chapter) feature a thin fleece glued to their back, to avoid fiber loss from the porous layer potentially mounted behind. A study on the exact effect of these fleeces on the modeling of the panel would be needed to truly be able to characterize a typical perforated facing.

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7. REFERENCES

1. ISO 10534-2, *Acoustics Determination of sound absorption coefficient and impedance in impedance tubes Part 2: Transfer-function method*. (1998). International Organization for Standardization, Geneva, Switzerland
2. Briere de La Hosseraye, B., Hornikx, M., & Yang, J. (2022). In situ acoustic characterization of a locally reacting porous material by means of PU measurement and model fitting. *Applied Acoustics*, 191, 108669.
3. Cox, T. J. (2002). *Acoustic Absorbers and Diffusers: Theory, Design and Application*. doi: 10.1201/9781482288254
4. Garai, M., & Guidorzi, P. (2000). European methodology for testing the airborne sound insulation characteristics of noise barriers in situ: Experimental verification and comparison with laboratory data. *The Journal of the Acoustical Society of America*, 108 (3), 1054.
5. Alvarez B, J. D., & Jacobsen, F. (2007). In-situ measurements of the complex acoustic impedance of porous materials. In Turkish acoustical society - *36th international congress and exhibition on noise control engineering, inter-noise 2007 Istanbul* (Vol. 6, pp. 4308–4317)
6. Atalla, N., & Sgard, F. (2007). Modeling of perforated plates and screens using rigid frame porous models. *Journal of Sound and Vibration*, 303 (1-2), 195–208
7. Carbajo, J., Ramis, J., Godinho, L., & Amado-Mendes, P. (2017). Modeling of grooved acoustic panels. *Applied Acoustics*, 120 , 9–14
8. Miki, Y. (1990). Acoustical properties of porous materials : Generalizations of empirical models-. Journal of the Acoustical Society of Japan (E), 11 (1), 25–28