DOI: 10.61782/fa.2023.0717

CHARACTERISATION OF PRESSURE-DEPENDENT SOUND ABSORPTION IN PERFORATED RIGID-FRAME POROUS MATERIALS

Théo Cavalieri[1,*] **Bart Van Damme**[1]

[1] Empa, Acoustics/Noise control, Ueberlandstrasse 129, Duebendorf, Zuerich, Switzerland

ABSTRACT

Porous materials is one of the most commonly-used classes of sound absorbers for modern acoustic treatments. However thin layers of these classical materials are not efficient at absorbing low-frequency sound waves, which is a technological shortcoming. Nonetheless, recent studies have shown that deep sub-wavelength acoustic absorption is achievable thanks to perforated foams which display extraordinary tortuosity [1]. Yet, at high sound pressure level (SPL), non-linearities of the surface impedance arise due to flow-separation at the vicinity of the perforations. Therefore, it is necessary to adapt existing porous material models for SPL-dependency. The proposed investigations are carried on experimentally, as several samples are tested for flow-resistivity as well as for absorption using impedance tube measurements. We observe and predict the change of effective fluid properties and Johnson-Champoux-Allard-Lafarge parameters with respect to SPL. The most significant of them is the increase of static air flow resistivity, which drastically changes the surface impedance of the porous medium, and inhibits the first quarter-wave mode. The proposed model accurately predicts the change in acoustic absorption of rigidly-backed perforated porous treatments.

Keywords: *porous material, equivalent fluid, non-linearity, surface impedance*

1. INTRODUCTION

In this work, we investigate how the sound absorption coefficient of perforated mineral foams is affected by high SPLs. While common porous materials such as glass-wool do not display strong non-linear features, perforated structures are known to exhibit non-linear regimes [2].

Moreover, classical porous material are usually modelled using an equivalent fluid approach, which itself is derived from a multiple-scale homogenisation approach [3]. More particularly, the Johnson-Champoux-Allard-Lafarge (JCAL) theory [4] provides the equivalent mass density ρ and bulk modulus B of such equivalent fluids for rigid-frame porous materials. Both these quantities are complex-valued and frequency-dependent. The JCAL model encapsulates the complete dynamics of wave propagation and dissipation into 6 parameters, which emerge from the local fields of temperature and particle velocity within the porous medium. The JCAL parameters are: the open porosity ϕ and thermal characteristic length Λ', which are both purely geometric quantities, the tortuosity τ^∞ and characteristic viscous length Λ which both result from the non-viscous fluid flow at high-frequencies, and finally the thermo-static and visco-static permeabilities, Θ^0 and K^0 which describe the temperature and particle velocity fields at $\omega \rightarrow 0$. The effective mass density captures visco-inertial effects, represented by K^0, τ^∞, and Λ, while the bulk modulus is related to the thermo-acoustic effects through parameters Θ^0 and Λ'.

This work aims to assess the variation of these parameters with respect to SPL. A first effect in response to high pressure gradients is the rise of air-flow resistivity σ, which can be directly measured. Furthermore, impedance tube measurements are performed in order to obtain the surface impedance Z_s of the perforated foam. An analysis

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*****Corresponding author**: theo.cavalieri@empa.ch.*

on linear and non-linear behaviour is carried out, in order to characterize the model's dependence on SPL.

This paper is organised as follows: first the experimental methods for flow-resistivity and acoustic impedance are described in Sec. 2. Then the non-linear effects on sound absorption are presented in Sec. 3. Finally, the discussions are given in Sec. 4.

2. MATERIALS & METHODS

In a first instance, we measure the pressure drop across the sample for a given fluid flow. From this data, the visco-static permeability K^0 and air-flow resistivity σ are directly derived using Darcy's law [5]:

$$\mathbf{v} = -\frac{K^0}{\eta}\boldsymbol{\nabla} p \, , \tag{1}$$

where the volume force due to gravity is neglected, $\mathbf{v}$ is the particle velocity, p the acoustic pressure, and η the dynamic viscosity of air. The static air-flow resistivity is then given by $\sigma = \eta/K^0$. From the measurements at different pressure-velocity couples (and enforcing the zero-pressure/zero-velocity point according to the standard ISO 9053-1), the visco-static permeability of the medium is obtained for a flow speed of $|\mathbf{v}_{\mathrm{ref}}| = 0.5\,\mathrm{mm.s}^{-1}$. This corresponds to an excess pressure $p_{\mathrm{ref}} = \rho_0 c_0 |\mathbf{v}_{\mathrm{ref}}| = 0.2\,\mathrm{Pa}$ and to a level $L_{\mathrm{ref}} = 80\,\mathrm{dB\,SPL}$. Figure 2**(a)** shows the normalised air-flow resistivity $\sigma(\mathbf{v})/\sigma(\mathbf{v}_{\mathrm{ref}})$ for different particle velocities of a sample made of 2 mm closed pores, 0.5 mm perforations every 5 mm. As observed on Fig. 2**(a)** the flow-resistivity σ increases with respect to the acoustic particle velocity, i.e., σ increases with the pressure gradient.

On the second hand, the perforated foam is tested in an impedance tube under plane wave excitation, as described in the standard ISO 10534-2. The test rig is the model Type-4206 provided by Brüel and Kjær[1] with diameters of $d = 100\,\mathrm{mm}$ or $d = 29\,\mathrm{mm}$. The acquisition of pressure signals is made using Type-4187 microphone pair[2], also provided by Brüel and Kjær. Photographs of both the flow-resistivity and impedance tube setups are shown in Fig. 1.

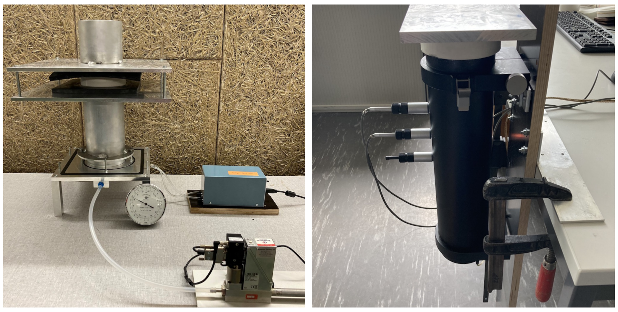

Figure 1. Test-bench for flow-resistivity measurement using pressurized chamber (left) and impedance tube set-up with two microphones (right).

3. NON-LINEAR SOUND ABSORPTION

In the reflection configuration where the porous material is rigidly backed, the total pressure field in the Kundt tube is related to the surface impedance of the sample. In the present case, the surface impedance of the perforated material is complex valued and reads $Z_{\mathrm{s}}(\omega) = R(\omega) + \mathrm{i}\chi(\omega) \in \mathbb{C}$, where R is the resistance and χ the reactance. The acoustic absorption coefficient is connected to the surface impedance [6, 7] by

$$\alpha(\omega) = 1 - \left| \frac{Z_{\mathrm{s}} - Z_0}{Z_{\mathrm{s}} + Z_0} \right|^2 \, , \tag{2}$$

with $Z_0 = \rho_0 c_0$ the characteristic impedance of free-air. The results on Fig. 2**(b)** evidence the non-linearity on the acoustic absorption coefficient $\alpha(\omega)$, as increasing the SPL drastically changes the absorption behaviour. At low sound levels, i.e., less than 80 dB SPL the non-linearity is absent, thus the linear impedance is written $Z^{(\mathrm{l})}(\omega) = \lim\limits_{\mathrm{SPL} \leq 80} Z_{\mathrm{s}}(\omega)$, from which we redefine the surface impedance as $Z_{\mathrm{s}}(\omega) = Z^{(\mathrm{l})}(\omega) + Z^{(\mathrm{nl})}(\omega)$ leading to the expanded form of the impedance which reads

$$Z_{\mathrm{s}}(\omega) = \left(R^{(\mathrm{l})} + R^{(\mathrm{nl})} \right) + \mathrm{i} \left(\chi^{(\mathrm{l})} + \chi^{(\mathrm{nl})} \right) \, . \tag{3}$$

Since both ϕ and Λ' are purely geometric, and τ^∞ and Λ describe the high-frequency asymptotic of the mass density, only the static values of the permeabilities are subject to encapsulate the non-linearity observed at low frequencies. However, as the thermo-static permeability introduced by Lafarge [4] plays a negligible role in the acoustic absorption, the visco-static permeability K^0 is considered

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[1] https://www.bksv.com/en/transducers/acoustic/acoustic-material-testing-kits

[2] https://www.bksv.com/en/transducers/acoustic/microphones

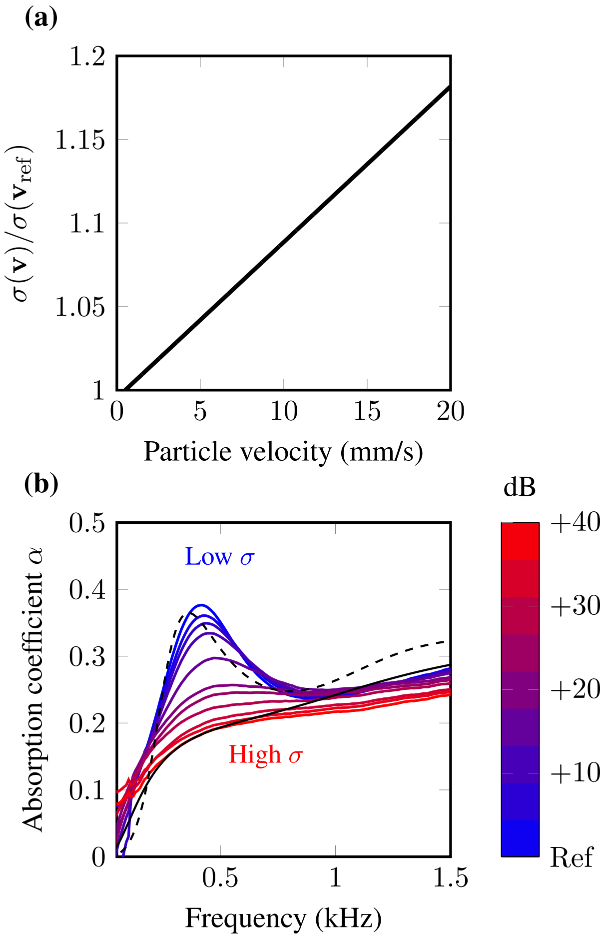

Figure 2. **(a)** Normalised static air-flow resistivity with respect to particle velocity. **(b)** Sound absorption coefficient $\alpha(\omega)$ for different SPL (blue to red), simulated acoustic absorption with Ref.-σ (dashed black), and 10×Ref.-σ (solid black).

to be the principal driving factor of the non-linearity, that is $\partial_L K^0 \neq 0$.

As a result, the visco-inertial permeability $K(\omega, L)$ of the mineral foam becomes SPL-dependent, and is a complex and frequency-dependent quantity. This leads to the mass density $\rho(\omega, L)$ of the equivalent fluid to also become SPL-dependent, while the bulk modulus $B(\omega)$ remains unchanged, as this quantity solely depends on ϕ, Λ', and Θ^0.

4. CONCLUSIONS

Perforated mineral foams have shown their ability to provide strong acoustic absorption in sub-wavelength regimes, making these structures viable for thin low-frequency absorbers. Such materials are well described by multiple-scale homogenisation theory and finally by the JCAL theory. This allows to depict the mineral foam as an equivalent fluid having complex and frequency-dependent properties. However, the response of micro-perforated structures is known to display non-linear behaviours at high SPLs. In this work we investigate the non-linearity in perforated porous materials and establish its connection to changes in effective properties of the equivalent fluid, and more generally the change in flow resistivity to explain the acoustic absorption.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge M. Haselbach, E. Pieper, M. Kappeli, U. Pachale at Empa Dübendorf, and U. Gonzenbach, P. Sabet, and P. Struzenegger from de Cavis AG. This work is jointly funded by Innosuisse project 56633.1 and de Cavis AG.

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