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Technical note

Acoustic modeling of perforated concrete using the dual porosity theory

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ABSTRACT

Perforated concrete shows nowadays a high potential for many construction and building engineering applications. This work is devoted to the analysis of the acoustic properties of perforated concrete made from arlite lightweight aggregates. Concrete produced from these materials is an environmentally friendly alternative to traditional materials and offers a higher durability, excellent strength-to-weight ratio and low cost. In particular, it is shown that the acoustic behavior of perforated concrete can be modeled using a dual porosity approach based on the knowledge of the non-acoustic properties of the matrix granular material and geometrical data. To this end, various non-perforated and perforated samples were prepared and characterized in an experimental test facility, their acoustic properties being determined through the transfer function impedance tube method. Experimental and estimated results related to the acoustic properties of a number of prepared specimens are presented, showing a good agreement. Results suggest that this approach is suitable for practical design of such materials as part of noise control systems.

1. Introduction

Improved acoustic performance of the constructive solutions is of great interest in building [1] and environment [2] science. Porous materials, such as fibers and foams, are frequently employed to reduce transmission of airborne and impact noise in a large number of these solutions. However, such materials have a low structural strength and durability, especially when exposed to adverse weather conditions (heavy rain, snow storms, strong wind breezes, etc.), showing a significant decrease in their acoustic performance over time. Alternatively, it is common to use elements made entirely from concrete, whose higher stiffness and structural strength prevent the need for additional frames or supports, their main drawbacks being the heavy weight and low sound absorption performance. Porous concrete mitigates these latter disadvantages [3], as it enables to work with different porosities to reduce weight and also to achieve an acceptable sound absorption, adapted in each case to the structural design constraints. Several models exist in the literature [4–6] for acoustic modeling of single porosity granular media such as porous concrete. Horoshenkov and Swift [7] proposed a simple and reliable model to predict the acoustic properties of granular materials, which has been successfully used later to analyse different types of porous concrete [8–10]. A further step to obtain a significant reduction of the overall weight of the porous concrete, and therefore its associated cost, while preserving the above advantages, is to drill holes in the matrix material, resulting in perforated concrete.

Perforated concrete consists of a compound of mortar and coarse aggregate, on which a series of holes or perforations are made, usually bonded onto a high-density concrete backing. The decorative and aesthetic effect of a panel of this type turns it into an attractive choice for multiple indoor (community areas, gymnasiums, etc.) and outdoor (such as noise barriers or tunnels) applications in which noise control is important and a positive visual impact is desired. While the workability thereof is not very good (moulds or matrices are often used), in recent years new manufacturing methods that use sophisticated digital techniques have been developed, greatly facilitating this work [11–13]. These methods allow to produce panels that yield different hole sizes and spatial patterns, which also prompts their design with acoustic purposes.

As a matter of fact, perforated panels are commonly used in noise control applications, the sound absorption phenomenon being produced by viscous losses in their pores or holes. There are numerous models [14–17] to predict the acoustic behavior of

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these systems, which may be determined from their orifice diameter, perforation ratio (or porosity) and panel thickness. Although some authors have investigated more complex configurations [18–21], those typically studied consist of a flat rigid panel with periodically arranged circular holes. Nevertheless, when the non-perforated part of the panel (i.e. the matrix material), is itself a considerably porous material (e.g. perforated concrete), extra loss mechanisms must also be considered. The material that results from drilling a porous medium is also known as a meso-perforated or dual porosity material, since it is composed of two porous networks of different characteristic size. Olny and Boutin [22], based on a previous work in the field of geophysics [23] that uses a homogenization method to study the acoustic wave propagation in these materials, proposed a more generic model to describe their macroscopic behavior. Subsequently, several authors [24–27] have applied this theory to analyse the sound absorption properties of different dual porosity materials, experimentally verifying that their sound absorption coefficient can be estimated satisfactorily with this model. While the incorporation of resonator tubes [28] and Helmholtz resonators [29] in porous concrete has been investigated experimentally in the literature, to the authors' knowledge, little work has been done concerning their acoustic modeling.

This work presents results corresponding to the experimental characterization of perforated concrete and proposes the application of a dual porosity approach for the prediction of its acoustic properties. For this purpose, different samples of non-perforated and perforated concrete made from arlite lightweight aggregates were prepared. The non-acoustic properties of the non-perforated specimens were determined beforehand and then used as input data in the models proposed by Horoshenkov and Swift [7] and by Olny and Boutin [22] to predict the acoustic properties of both types of samples. These predictions are compared with experimental results obtained from measurements in a plane wave tube, obtaining a good correlation.

This work is organized as follows. In Section 2, the properties describing the acoustic behavior of rigid porous media are briefly presented, along with two modeling approaches to predict these properties in granular media: Horoshenkov and Swift model [7], and in double porosity media, Olny and Boutin model [22]. Preparation of non-perforated and perforated concrete specimens, and the experimental procedures used to characterize them, is described in Section 3. Section 4 discusses the experimental results for the non-acoustic properties of the non-perforated specimens and their relationship to their measured acoustic properties. The acoustical data are also compared against the theoretical predictions, these latter being validated for both non-perforated and perforated materials. Finally, the main conclusions are summarized in Section 5.

2. Theoretical formulation

2.1. Acoustic modeling of rigid porous media

Acoustic wave propagation in porous media saturated with air is difficult to study on a microscopic scale due to the complex geometry of the structure. Instead, it is common to describe the behavior of sound waves through these media adopting a macroscopic formulation and considering a rigid skeleton in order to model the material as an equivalent fluid. This simplified approach will serve for the models adopted in this work, and will allow the derivation of frequency-dependent complex expressions for two important acoustic properties of these materials, namely characteristic impedance, Z_C, and wave number, k [30]

$$Z_C = \sqrt{\rho K} \tag{1}$$

$$k = \omega\sqrt{\rho/K} \tag{2}$$

where ρ and K are the dynamic density and bulk modulus of the equivalent fluid, respectively, and ω is the angular frequency. These two properties, ρ and K, represent the viscous friction and thermal loss mechanisms at the pore walls of the material, respectively, and are related to the size of pores and the corresponding porosity.

Eqs. (1) and (2) can then be used to calculate the surface impedance, Z_S, and the sound absorption coefficient under normal incidence, α, of a hard-backed porous material layer of thickness d [31]

$$Z_S = -jZ_C \cot(kd) \tag{3}$$

$$\alpha = 1 - \left|\frac{Z_S - \rho_0 c_0}{Z_S + \rho_0 c_0}\right|^2 \tag{4}$$

with ρ_0 and c_0 being the density and the sound propagation velocity in air, respectively, and j the imaginary unit.

2.2. Horoshenkov and Swift model for granular media

Most porous materials are composed of pores of variable shape and whose size normally obeys a certain statistical distribution. While the variation of the pore shape is not that important, this statistical distribution can have a significant effect on the acoustic properties of the material. Horoshenkov and Swift [7] proposed a model for granular media with log-normally distributed pore size which is based on the use of four easily measurable non-acoustic properties (open porosity, flow resistivity, tortuosity and standard deviation of the pore size) to predict the acoustic properties of the material. The successful use of this model to analyse different types of porous concrete [8–10] has motivated its choice to predict the acoustic properties of the matrix material from which the perforated concrete is made. Following the work by Horoshenkov and Swift [7] it is possible to derive the dynamic density and the bulk modulus for a granular material from

$$\rho = \frac{\alpha_\infty}{\phi}\left(\rho_0 - j\frac{\sigma\phi}{\omega\alpha_\infty}\tilde{F}(\omega)\right) \tag{5}$$

$$K = \frac{\gamma P_0}{\phi}\left(\gamma - \frac{\rho_0(\gamma-1)}{\rho_0 - j\frac{\sigma\phi}{\omega\alpha_\infty N_P}\tilde{F}(N_P\omega)}\right)^{-1} \tag{6}$$

where α_∞ is the tortuosity, ϕ the open porosity, σ the flow resistivity, γ the ratio of specific heats, P_0 the atmospheric pressure and N_P the Prandtl number. $F\sim(\omega)$ is the viscosity correction function, which can be presented in the form of a Padé approximation as

$$\tilde{F}(\omega) \cong \frac{1 + a_1\varepsilon + a_2\varepsilon^2}{1 + b_1\varepsilon} \tag{7}$$

in which $a_1 = \theta_1/\theta_2$, $a_2 = \theta_1$, $b_1 = a_1$ and $\varepsilon = (j\omega\rho_0\alpha_\infty/(\sigma\phi))^{1/2}$ is a dimensionless parameter. In these latter definitions, $\theta_1 = (4/3)e^{4\xi} - 1$ and $\theta_2 = (1/\sqrt{2})e^{3\xi/2}$ are the shape factors when a circular pore geometry is assumed, where $\xi = (\sigma_p \ln 2)^2$ and σ_p is the standard deviation in the log-normally distributed pore size.

2.3. Olny and Boutin model for double porosity media

Let us now consider a representative elementary volume of a double porosity or meso-perforated material such as that presented in Fig. 1, composed of two periodic interconnected networks of pores whose characteristic sizes l_M and l_m differ, both being small compared to the wavelength of the sound wave of interest. Hereinafter, the subscripts M and m refer to the meso-pores and the micropores of the double porosity material, respectively, the characterized size of the former being much larger than that of the latter.