A LITERATURE REVIEW FOR THE ANALYSIS OF VIBORACOUSTIC PROPERTIES OF PERIODIC INCLUSIONS IN POROUS MATERIALS

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ABSTRACT

The design based on periodic elements is a powerful strategy for the achievement of lightweight sound packages and represents a convenient solution for manufacturing aspects. An interesting research target is the inclusion of vibroacoustic design rules at early stage of products development through the use of porous media with periodic inclusions, which exhibit proper dynamic filtering effects; this offers different applications in transportation (aeronautics, space, automotive, railway), energy and civil engineering sectors, where both weight and space, as well as vibroacoustic integrity and comfort, still remain as critical issues. This work is a literature review which mainly focuses on three aspects concerning periodic inclusions in porous materials: the concept of substitution of a fluid layer for a porous layer, the Transfer Matrix Method and the descriptions of two alternatives to multi-layering.

1 SUBSTITUTION OF A FLUID LAYER FOR A POROUS LAYER

1.1 Description of sound propagation in porous media

On a microscopic scale, sound propagation in porous materials is generally difficult to study because of the complicated geometries of the frames. Only the mean values of the quantities involved are of practical interest. The averages must be performed on a macroscopic scale, on a homogenization volume with sizes large enough to become meaningful. At the same time, these sizes must be much smaller than the acoustic wavelength. The description of sound propagation in porous material can be complicated by the fact that sound also excites and moves the frame of the material. If the frame is motionless, in a first step, the air inside the porous medium can be replaced at the macroscopic scale by an equivalent free fluid. This equivalent fluid has a complex effective density ρ and a complex bulk modulus K. The wave number k and the characteristic impedance Z_c of the equivalent fluid are also complex [1].

1.2 An empirical model provided by Delany and Bazley

The k and Z_c have been measured by Delany and Bazley (1970) for a large range of frequencies in many fibrous materials with almost unit porosity. According to these measurements, the quantities k and Z_c depend mainly on the angular frequency ω and on the flow resistivity σ of the material. Good fits for k and Z_c have been obtained:

$$Z_c = \rho_0 c_0 [1 + 0.057X^{-0.754} - j0.087X^{-0.732}]. \tag{1}$$

$$k = \frac{\omega}{c_0}[1 + 0.0978X^{-0.700} - j0.189X^{-0.595}]. \tag{2}$$

where ρ_0 and c_0 are the density of air and the speed of sound in air; X is a dimensionless parameter which is suggested to be valid within the range $0.01 < X < 1.00$.

These relations will not provide perfect predictions of acoustic behaviour of all the porous materials in every frequency ranges. Nevertheless, the laws of Delany and Bazley are widely used and can provide reasonable orders of magnitude for Z_c and k. With fibrous materials, which are anisotropic, the flow resistivity must be measured in the direction of propagation for waves travelling in either the normal or the planar direction. The case of oblique incidence is more complicated. It should be pointed out that after the work by Delany and Bazley, several authors suggested slightly different empirical expressions of k and Z_c for specific frequency ranges and for different materials [1].

1.3 Mesostructure based models

In the case of common porous materials, an analytical description of sound propagation that takes into account the complete geometry of the microstructure is not possible. This explains why the models of sound propagation in these materials are mostly phenomenological and provide a description only on a large scale [1]. In 1987, Johnson, Koplik and Dashen proposed a semi-phenomenological model to describe the complex density of an acoustical porous material with a motionless skeleton having arbitrary pore shapes; 4 parameters are involved in the calculation of this dynamic density: the open porosity ϕ, the static air flow resistivity σ, the high frequency limit of the tortuosity $\alpha\infty$ and the viscous characteristic length Λ. In 1991, Champoux and Allard introduced an expression for the dynamic bulk modulus for the same kind of porous material based on the previous work by Johnson et al.; 2 parameters are involved in the calculation of this dynamic bulk modulus: the open porosity ϕ and the thermal characteristic length Λ'. In Biot-Allard model, which includes the description of the skeleton movement, a material is characterized by a number of conventional mechanical parameters (density of the skeleton, Young's modulus of the skeleton in vacuum, Poisson's coefficient of the skeleton in vacuum, structural damping), as well as by specific parameters called Biot parameters (porosity, resistivity, tortuosity, viscous characteristic length, thermal characteristic length).

2 MULTI-LAYERED SYSTEMS WITH POROUS MATERIALS MODELED USING THE TRANSFER MATRIX METHOD

The description of the acoustic field in a porous layer is complicated by the presence of the shear wave and the two longitudinal waves. In a layered medium with porous layers, elastic solid layers and fluid layers, a complete description can become very difficult. A matrix representation of sound propagation well consolidated in literature is described here. The stratified media are assumed laterally infinite. They can be of different nature: elastic solid, thin plate, fluid, rigid porous, limp porous and poroelastic. However, the different media are assumed to be homogeneous and isotropic. Figure 1 illustrates a plane acoustic wave impinging upon a material of thickness h, at an incidence angle θ. Various types of waves can propagate in the material, according to their nature. The x_1 component of the wave number for each wave, propagating in the finite medium, is equal to the x_1 component k_t of the incident wave in the free air:

$$k_t = k \sin\theta. \tag{3}$$

being k the wave number in free air. Sound propagation in the layer is represented by a transfer matrix $[T]$ such that

$$\boldsymbol{V}(M) = [T]\boldsymbol{V}(M'). \tag{4}$$

Where M and M' are set close to the forward and the backward face of the layer, respectively, and where the components of the vector $\boldsymbol{V}(M)$ are the variables which describe the acoustic field at a point M of the medium. The matrix $[T]$ depends on the thickness h and the physical properties of each medium [1].

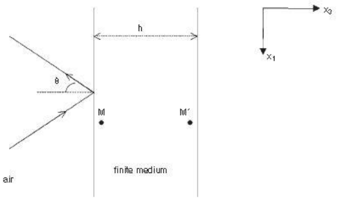

Figure 1. Plane wave impinging on a domain of thickness h.

3 ALTERNATIVES TO MULTI-LAYERING

Although porous materials are commonly used for vibroacoustic applications, they suffer from a lack of absorption at low frequencies compared to their efficiency at higher ones. This difficulty is usually overcome by multi-layering. However, while reducing the impedance mismatch at the air-material interface, the efficiency of such devices relies on the allowable thickness [2].

3.1 Embedding rigid inclusions

One way allowing to enhance the low frequency efficiency of sound packages consists in embedding periodic rigid inclusions in a porous layer [3]. If the radius of these periodic inclusions is comparable with the acoustic wavelength, then an increase of the absorption coefficient can be observed. In [3], the influence of the periodic inclusions on the absorption coefficient was explained by excitation of additional acoustic modes which dissipate acoustic energy. When the porous layer is backed by a flat rigid surface and when only one inclusion per unit cell grating is embedded, an additional trapped mode can be excited. This results in a quasi-total absorption peak at a frequency below that of the usual quarter-wavelength resonance in the homogeneous layer case. Other interesting studies related to volume heterogeneities are in [4, 5-8].

3.2 Embedding Helmholtz resonators

The homogenization theory cannot be applied to cellular material made of large periodic unit-cell. In this case, a low frequency solution to improve the acoustic efficiency of passive open-cell porous materials is to embed Helmholtz resonators (HR) in the porous matrix. Doing so, at the Helmholtz resonance frequency, the transmission loss is greatly improved and the sound absorption of the host material is decreased if it is made of a highly sound absorbing material. One of the first works describing such structure is a patent filed in by Borchers et al. [6]. Much later, Sugie et al. [7] proposed a similar heterogeneous material made of a fibrous sound absorbers with resonant inclusions. More recently, the acoustic community had shown a keen interest in the equivalent material (also called effective material or metamaterial) presenting a negative bulk modulus at the HR resonance frequency [8]. In [9] the sound absorption efficiency is investigated in case of rigid backed acoustic foams with resonant split hollow cylinder inclusions. Under the assumption that the HR periodicity is much smaller than the acoustic wavelength, the resonant materials are usually modelled as homogenized equivalent material with modified bulk modulus to account for the presence of the resonant inclusion [8]. However, as already stated, cellular resonant material with large periodicity obviously prevents the use of the homogenization method. In this case, the orientation of the HR neck may have a strong influence on the sound absorption behaviour of the resonant material [9, 10].

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