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Considerations on the sound absorption of non locally reacting porous layers

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A B S T R A C T

The sound absorption coefficient describes the ability of a porous material to absorb energy. It depends on the intrinsic acoustic properties of the porous material and is sensitive to the type of the wave-front impinging on the porous layer. From the total sound pressure field on the porous material, it is possible to obtain the sound absorption coefficient by separating the incident sound pressure field from the reflected one at the air/porous layer interface. The purpose of this work is to compare the ability of current analytical models to estimate the sound absorption coefficient of porous layers and others acoustical properties such as surface acoustic impedance and reflection coefficient, by using Finite Element Method (FEM) simulations as reference. This study also shows how the sound absorption coefficient of the porous layer varies when a spherical wave-front impinges on its surface.

1. Introduction

Porous materials are used in many outdoor and indoor sound propagation applications for noise control. In order to predict their effectiveness, it is necessary to know their acoustic characteristics. The surface acoustic impedance is one of the most important parameters used both directly in numerical simulation programs (e.g. FEM, BEM, etc.) as boundary condition and in experimental tests to obtain sound absorption coefficients.

The measurement of the surface acoustic impedance can be performed by using the impedance tube or free field measurement techniques. The latter are generally used when it is impossible to take samples from the tested material or to avoid resonance phenomena due to the compression of the specimen edges. These techniques allow us to study the acoustical behavior of the material at different incidence angles as well. In real case however, some difficulties in the control of the wave-front are also due to the loudspeaker characteristics (e.g. break-up modes, directivity, etc.).

During the last few years, many researchers have engaged themselves to understand how the boundary conditions, the edge diffraction effects, the probe type, its positioning and errors associated with the precision of the used instrumentation can affect the surface acoustic impedance measurement [1–11]. Some of them have investigated the consequences of the measured sound absorption coefficient due to changes in the measurement set-up by using numerical Boundary Element Method (BEM) technique [4,5,8]. When required, all the above-mentioned works assume the hypothesis of a Locally Reacting (LR) porous material. Therefore, a sound wave can propagate within the porous layer especially along the normal direction at the material surface. As a consequence, the surface acoustic impedance of the sound-absorbing layer is the same at each location on the porous material surface regardless of the wave-front shape or the incidence angle of the sound wave.

Instead, when the porous layer behaves as a Non-Locally Reacting (NLR) material, the surface acoustic impedance depends also on the incidence angle of the sound wave. Therefore, the issue of the acoustical behavior of the porous material is more difficult to be dealt with [11,12].

Since the surface acoustic impedance can be obtained starting from the values of the sound pressure measured or esteemed on the material surface, it is relevant to have an analytical model able to predict the sound pressure field above a porous layer in order to assess the sound absorption coefficient or to judge the reliability of the surface acoustic impedance measurements.

From the general formulation suggested by Brekhovskikh and Godin [13], various solutions have been proposed to solve numerically the problem of the sound pressure field generated by a point source in air above a rigid porous layers. For example, the steepest descent integration method, suggested by the same authors, give an approximate solution for small incidence angles of sound waves and high distance of the sound source from the porous layer. Chien and Soroka proposed the modified steepest descent integration

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method (pole subtraction method) as a tool to obtain the sound pressure field due to a point source above a LR plane boundary [14]. Nobile and Hayek instead, developed a new solution in the form of an asymptotic series to solve this issue [15]. Di and Gilbert approached a description similar to the above-mentioned method by using Laplace transform formulation of an image source distribution [16]. It is worth noting, however, that Di and Gilbert's solution exactness depends on the numerical integration, while solutions proposed by other authors are approximations of the sound pressure field above a porous layer. The pole subtraction method is typically used in outdoor sound propagation [11,17] and then tested for various porous materials via heuristic modifications [18] to take into account the variability of the surface acoustic impedance with the incidence angle of sound wave. A thorough discussion of the frequency range when Chien and Soroka model, as modified by Li et al., can be applied, is reported in reference [19].

Allard et al. proposed a measurement method at grazing incidence in order to adapt the pole subtraction method for NLR material as well [20,21]. However, an evaluation of the sound pressure field generated by a point source above a NLR porous layer, backed by a rigid surface, was previously developed by Allard et al. starting from porous material properties (i.e. complex density and wave number) [22].

In recent works, an asymptotic solution for the sound pressure field above an impedance plane due to a monopole sound source has also been developed along with an efficient calculation method [23,24].

The purpose of this work is to compare the ability of analytical models currently available in the literature to estimate the surface acoustic impedance, the reflection and the absorption coefficient of porous layers backed by a rigid surface. In particular four analytical models have been considered, respectively proposed by Nobile and Hayek [15], Di and Gilbert [16], Chien and Soroka [14] as modified by Li et al. [18] and Allard et al. [22]. Acoustic results provided by a FEM model has been considered as a reference. Porous materials have been simulated as rigid frame porous materials by using Johnson et al. [25] and Lafarge et al. [26] models to calculate the complex density and the dynamic compressibility, respectively.

This study was focused just on the air-flow resistivity effects while the others properties were held constant. Obviously, beyond air-flow resistivity, also others parameters (e.g. porosity, tortuosity, viscous and thermal characteristic length, elastic property) modify the acoustic behavior of the porous material but this assumption does not affect the generality of the discussion.

2. Theoretical models for a layer of finite thickness backed by impervious and rigid surface

In this section, the theoretical models used in this work will be briefly discussed. All of them refer to a spherical incident wave-front. However, when the distance between the sound source and the surface material is large compared to the wavelength, the wave-front tends to be planar. For completeness, the simple plane-wave model is introduced.

2.1. Plane-wave model

The plane-wave model is the simplest model for the prediction of the surface acoustic impedance from the properties of a porous material. If the wave-front impinging on the surface of a porous material is planar, it is possible to estimate the surface acoustic impedance from the simple relation:

$$Z_{s,plane} = -jZ_m \frac{k_m}{k_{mz}} \cot(k_{mz}d), \tag{1}$$

were Z_m and k_m are respectively the characteristic impedance and the complex wave number of the porous material, d is its thickness and k_{mz} is the projection of the wave number orthogonal to the surface of the material. k_{mz} can be calculated from Snell's law:

$$k_{mz} = \sqrt{k_m^2 - k_{mx}^2} = \sqrt{k_m^2 - k_{0x}^2} = \sqrt{k_m^2 - k_0^2 \sin^2\vartheta_0}, \tag{2}$$

with k_{mx} and k_{0x} projections of the wave number parallel to the porous material surface evaluated in the material and in the air, respectively, k_0 wave number in the air and ϑ_0 angle of incidence which the plane wave-front forms with the normal at the porous material surface. If the material is LR, $k_{mz} \rightarrow k_m$ and Eq. (1) is similar to that for normal incidence. From the surface acoustic impedance Z_s, it is possible to obtain the complex reflection coefficient:

$$R_s = \frac{Z_s - \frac{Z_0}{\cos(\vartheta_0)}}{Z_s + \frac{Z_0}{\cos(\vartheta_0)}}, \tag{3}$$

where for plane wave-front, $Z_s = Z_{s,plane}$ and $Z_0 = \rho_0 c$ with ρ_0 and c, respectively, the air density and the sound speed in air. The complex reflection coefficient knowledge gives the sound absorption coefficient by the simple relation:

$$\alpha = 1 - |R_s|^2. \tag{4}$$

2.2. Nobile and Hayek model

One of the most widely used models for predicting the sound pressure field generated by a point source above a porous material is given by Nobile and Hayek. This model has been developed for LR materials so that the acoustic impedance is constant over the porous material surface and equal to the normal surface acoustic impedance. An expression valid for any angle of incidence can be found in [22] and is reported as follows:

$$p(R) = D\left(\frac{e^{-jk_0 r_1}}{r_1} + \frac{e^{-jk_0 r_2}}{r_2} + \frac{4jk_0\beta B e^{-jk_0 r_2}}{\beta + \cos(\vartheta_0)} \int_0^\infty \frac{e^{jk_0 r_2 (q^2 + 2Bq)}}{\sqrt{1 - (q^2/H) - (2Bq/H)}} dq\right), \tag{5}$$

where

$$B = j[1 + \beta\cos\vartheta_0 - (1-\beta)^{1/2}\sin\vartheta_0]^{1/2},$$

$$H = 1 + \beta\cos\vartheta_0 + (1-\beta)^{1/2}\sin\vartheta_0.$$

The meaning of the parameters appearing in Eq. (5) and in the following introduced models is shown in Fig. 1; in particular, r_1 and r_2 are the distances between the receiver and the sound source and the receiver and the image sound source respectively, $\beta = 1/Z_s$ is the surface acoustic admittance and D is a factor that takes into account the sound source level.

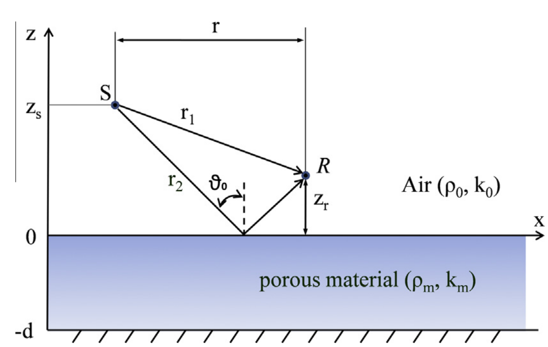

Fig. 1. Sketch of point source and receiver positions on a high air-flow resistivity porous material backed by a rigid and impervious surface.