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Errors when assuming locally reacting boundary condition in the estimation of the surface acoustic impedance

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ABSTRACT

Numerical simulations usually require boundary conditions in terms of surface acoustic impedance. The surface acoustic impedance depends on the porous material acoustic properties (e.g., characteristic impedance and wave number) and its thickness as well as the type of wave front impinging on its surface. The locally reactive behaviour hypothesis is often assumed to simplify the choice of proper boundary conditions assigning a constant acoustic impedance value on the porous material surface at a given frequency and for each angle of sound incidence. This hypothesis is also used in measurement procedures or for the estimation of the edge effects.

In this paper, it is shown that, in general, a porous material behaves partly as a locally reactive and partly as a non-locally reactive material depending on the ratio between the sound velocities in the free air and in the porous material. By using numerical FEM simulations it is shown that, given a porous material, the acoustic impedance may change or not along the material surface depending on the type of wave front that impinges on its surface.

The error when assuming the locally reactive behaviour for porous materials backed by a hard surface and planar incident wave front to compute surface acoustic impedance values has been investigated comparing results yielded by theoretical models available in the literature and the one proposed for non-locally reactive behaviour materials. The last one is validated by means of FEM simulations and experimental results.

1. Introduction

This paper deals with an important issue related to the behaviour of the surface acoustic impedance of a porous material backed by a hard surface. Usually theoretical models and/or measurement techniques for assessing the surface acoustic impedance require two main hypotheses: the locally or non-locally reactive behaviour of the porous material and the type of wave front (planar or spherical) impinging on its surface.

A locally reactive behaviour (LRB) material can be described as constituted by straight unconnected pores (i.e., the simple Rayleigh model) so that the sound propagation inside each pore depends only on the sound pressure above it [1–3]. This leads to a surface acoustic impedance independent of the type of wave front and therefore of the incidence angle [4]. In other words, sound pressure acting at a point on the material surface causes a reaction (i.e., sound reflection) in that point only. This implies that the reflectivity function is a delta pulse in the space domain and its spatial Fourier transform to the wavenumber domain is therefore "white," meaning that for a certain frequency the reflection coefficient is angle-independent [5]. On the contrary, when pores are interconnected, the sound field inside one pore generally depends also on the sound pressure above another different pore and the surface acoustic impedance depends on the angle of sound incidence. This is the case of non-locally reactive behaviour (NLRB) materials, or "extended reaction materials" [6]. In this case, the airflow resistivity plays an important role in the behaviour of the porous material [7–9].

In general, the behaviour of a porous material having a complex pore structure (e.g., fibrous, open cell material) can be studied by considering the porous material as an equivalent fluid [1]. When the complex sound velocity inside the material is much smaller than that in the free air, the internally travelling wave can only propagate orthogonally to the surface of the material. As a consequence, apart from the edge effect, the acoustic impedance is constant on its surface at a given frequency and therefore an LRB can be assumed. On the contrary, for NLRB materials, the internally travelling wave can propagate along different directions. This

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implies that the acoustic impedance can change over the surface of the porous material depending on the type of wave front. If the latter is planar, the angle of sound incidence is the same along the material surface and therefore also the surface acoustic impedance. Otherwise, if the angle of sound incidence changes, as for a spherical wave front, the surface impedance changes over the surface of the porous material. In this case, a local impedance value at every surface point should be introduced.

The surface acoustic impedance is affected by the above-mentioned hypotheses in a complex way. This is shown by means of FEM numerical simulations for a porous material having different airflow resistivity values, highlighting that a porous material behaves partly as NLRB material and partly as LRB material as also noted by Li and Hodgson experimentally [10].

The issues raised in this paper are encountered, for example, in BEM numerical simulations where boundary conditions are required. In order to make numerical simulations simpler, LRB is assumed for the porous material [8,11] assigning only one value of the surface acoustic impedance. For NLRB material, the latter can change with the height of the sound source, resulting in a time-consuming calculation. A different numerical method can be used to overcome these difficulties such as the wave–theory-based model derived from the so-called WRW scheme [5].

Except for special cases, measurement techniques of the surface acoustic impedance also must take into account the LRB or NLRB and sphericity of the sound field [8,12,13]. However, analytical models introduced to predict the sound field above a porous layer are usually based on the LRB hypothesis [14–20]. This may yield errors during the measurement of the surface acoustic impedance [7].

The LRB hypothesis is also used for assessing the so-called "edge effect". As shown by Thomasson [21], a radiation impedance of the scattered wave in series with the normal surface impedance must be considered to take into account the edge effects for the sound absorption coefficient assessment. Mechel [22] quantifies the error in the evaluation of the sound absorption coefficient for a strip and a rectangular porous material with respect to an endless porous material, showing that the error increases with the angle of sound incidence. Both authors assume the hypothesis of plane wave and LRB. On the other side, when the wave front is spherical, the influence of the edge effect is more complex [8,11,23].

In general, a theoretical model suitable to describe the surface acoustic impedance without assuming any hypothesis on the porous material behaviour is useful. In this paper, the authors propose the use of the propagation model above the material surface given by Allard et al. [24] for the prediction of the surface acoustic impedance. This model has been used successfully to improve the measurement techniques of the surface acoustic impedance for NLRB [7,24]. In particular, the surface acoustic impedance is assessed by the ratio on the material surface of the sound pressure and the particle velocity. The proposed model can be considered a general model to assess the surface acoustic impedance of porous materials from a theoretical point of view. These findings are obtained by comparing the surface acoustic impedance results given by the proposed model with those given both by FEM simulations and measurement results. Differences between the proposed model and simple LRB models are quantified for several heights of the sound source and for several thickness values of the porous material.

The paper is organised as follows. In Section 2, an FEM model and results of the sound pressure level above and inside the porous material are shown. Section 3 reports a brief description of the analytical models used to evaluate the surface acoustic impedance of a hard-backed porous material as well as the proposed model. In Section 4, a comparison among the surface acoustic impedance values obtained by the considered analytical models, FEM simulations, and measurements are shown. Finally Section 5 discusses the errors evaluated between the simple plane-wave LRB model and the proposed method.

2. FEM model

An FEM model was used to study the wave propagation above and inside a porous material. The latter was simulated with an equivalent fluid whose acoustic properties (e.g., wave number and characteristic impedance) were evaluated by means of the Miki model [25] because it requires only one parameter: airflow resistivity. The Miki model, instead of the well-known Delany-Bazley model [26], was used to prevent negative values of the real part of the surface acoustic impedance at low frequencies. Moreover, assigning suitable boundary conditions at the interface between free air and the porous sample, the FEM technique allows us to simulate the behaviour of the porous material without taking LRB assumption into account. To eliminate unwanted reflections from surrounding surfaces, a 3D FEM model was built to simulate a hemi-anechoic chamber enclosing the porous material sample (an anechoic chamber with a hard floor). The chamber surfaces, with the exception of the hard floor, are considered as an equivalent gas by using Delany and Bazley's power-law relations. In order to have an absorption coefficient value close to one above 50 Hz, suitable values for the wall thickness and the airflow resistivity were chosen; they were one meter and 800 rayl/m up to 500 Hz. For higher frequencies (up to 1000 Hz), a resistivity value of 1200 rayl/m was used. The dimensions of the air space enclosed in the simulated hemi-anechoic chamber were 4 m $\times$ 4 m $\times$ 2 m, and the porous material had a squared surface with a side length of 2 m and a thickness of 5 cm. A validation of FEM model is given in Ref. [27].

Simulations were performed for three values of the airflow resistivity 1000, 10,000, and 50,000 rayl/m, three values of the frequency 100, 500, and 1000 Hz and three values of the height of the sound source above the material surface 30, 75, and 150 cm. The sound source was simulated with a point source and, for all simulations, it was placed at the center of the sample, that is 2 m $\times$ 2 m.

As reported in Fig. 1, the surface acoustic impedance was obtained by computing the ratio between the sound pressure and the normal particle velocity evaluated on the surface of half a material side (1 m) at points 1 cm apart from each other (101 points).

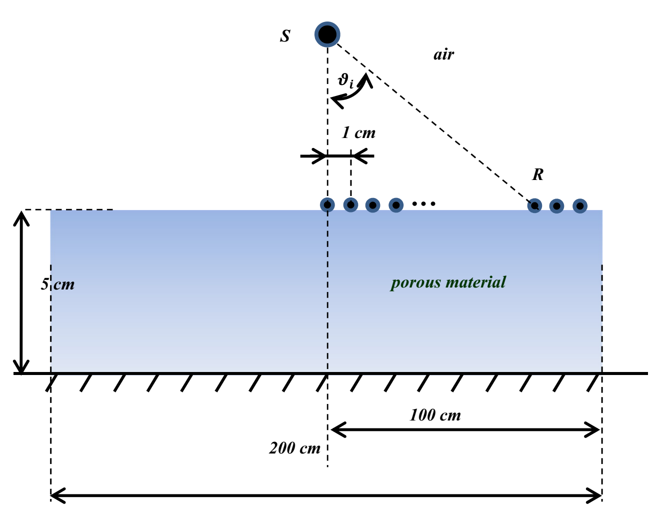

Fig. 1. Dimensions of the porous sample used for FEM model and positions of the sound source and receivers.