Applied Acoustics 133 (2018) 64–72

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical note

Experimental characterization of rigid porous material via the first ultrasonic reflected waves at oblique incidence

Mustapha Sadouki

Département des Sciences de la Matière, Faculté des Sciences et de la Technologie, Université Djilali Bounaama de Khemis-Miliana, BP. 44225 Ain Defla, Algeria

ARTICLE INFO

Keywords:
Characterization
Ultrasonic wave
Porous medium
Rigid frame

ABSTRACT

Enhanced ultrasonic method for the evaluation of acoustic parameters of air-saturated porous material is presented. This method is based on the direct and inverse problem of the reflection of an oblique incident wave from the surface of the porous medium with rigid frame. The interaction of the sound pulse with the porous material is described by the equivalent fluid model using the Johnson-Champoux-Allard approach (JCA) to describe the visco-inertial dissipative effects and the thermal effects inside the porous media. Four parameters are involved in the calculation of the dynamic density and the bulk modulus at high frequencies, namely the porosity ϕ, the high frequency limit of tortuosity α_∞, the viscous and thermal characteristic lengths Λ and Λ'. The sensitivity of each parameter on reflected waves from the surface of the porous medium is studied for different oblique angles of incidence. The advantage of the proposed method is that the inverted values of porosity, tortuosity, viscous and thermal characteristic lengths are simultaneously obtained by minimizing between the experimental and simulated reflected signals. Moreover, no relationship is assumed between the viscous and thermal characteristic lengths. The numerical and experimental validation of this method is presented and compared to the theoretical prediction.

1. Introduction

A porous material is a medium containing pores filled with a fluid (liquid or gas). The skeletal part is usually a solid. Many natural and made mediums such as rocks, soils, bones, plastic foams, fibrous materials, cements and ceramics can be considered porous materials. Among these materials, such as plastic foams and fibrous, are frequently used in the automotive and aeronautic industries and in the buildings trade to reduce noise and vibration pollution. Therefore, good acoustic performance is a desirable attribute in almost all types of buildings and is particularly important for residential buildings, schools and hospitals. The effectiveness of these porous materials in sound absorption is mainly based on their intrinsic properties. In this context, many mathematical models have been developed to predict the acoustic behavior of porous materials. Ultrasonic measurements [1–6,18–21] as well as Audio-frequency ones [7] can be used for description [1–6,18–21] and characterization [8–19] of porous media. To describe the visco-inertial dissipation effects within the porous medium, Johnson Koplik Dashen [1] proposed a semi phenomenological model to explain the complex density of an acoustical porous material with a rigid frame having arbitrary pore shapes. However, and based on the previous work of Johnson et al. [1], Champoux and Allard [2] proposed an expression for the dynamic bulk modulus to describe the thermal effects inside the porous medium. Johnson-Champoux-Allard (JCA) model predicts high and low frequencies performance and gives good prediction in intermediate frequencies range [5]. Four physical parameters namely; the porosity ϕ, the tortuosity α_∞, the viscous characteristic length Λ, and the thermal characteristic length Λ' are involved in the calculation of the dynamic density and bulk modulus in high frequency, the values of which are fundamental for the behavior of sound waves in these materials. Therefore, it is important to develop advanced methods and effective tools for their estimation. Various methods [1,7–18,21–27] have been developed for estimating these parameters. Some do not use acoustic waves are called direct methods [5,6,13,22,24,27,28] and other use sound waves are called indirect or inverse methods [7–12,14–21,23,25,26]. Solving the inverse problem [10,11,18–21,28] is a way that allows the determination of these acoustic parameters using transmitted or reflected ultrasonic waves. Previously, only porosity and tortuosity were easily obtained by using the reflected wave from the surface of the porous material [11]. In addition, the four acoustic parameters were simultaneously measured using waves transmitted [10] by air-saturated porous material.

In this work, an improved inverse method is proposed to determine these four parameters simultaneously by measurements of obliquely-reflected ultrasonic waves from the surface of the porous medium. A simple calculation in the frequency domain is presented to derive the

---

E-mail address: mustapha.sadouki@univ-dbkm.dz.

https://doi.org/10.1016/j.apacoust.2017.12.010
Received 27 August 2017; Received in revised form 7 November 2017; Accepted 11 December 2017
0003-682X/

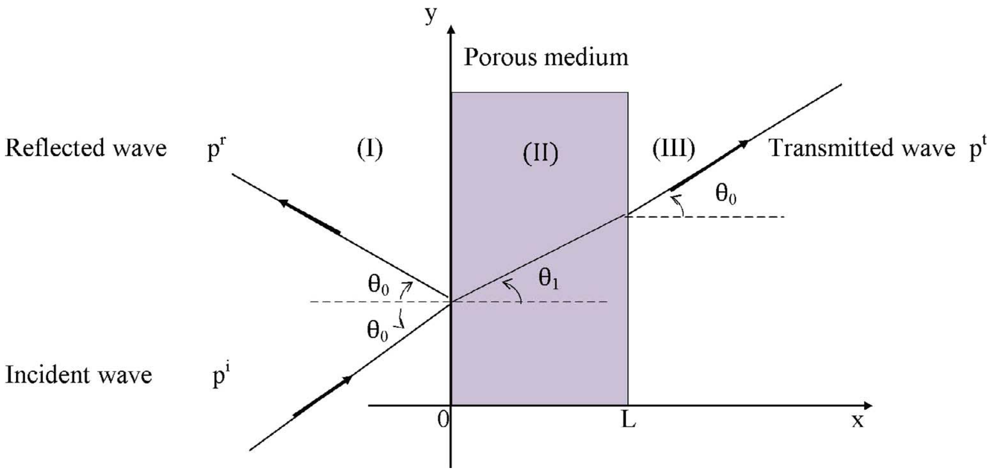

Fig. 1. Geometry of the problem.

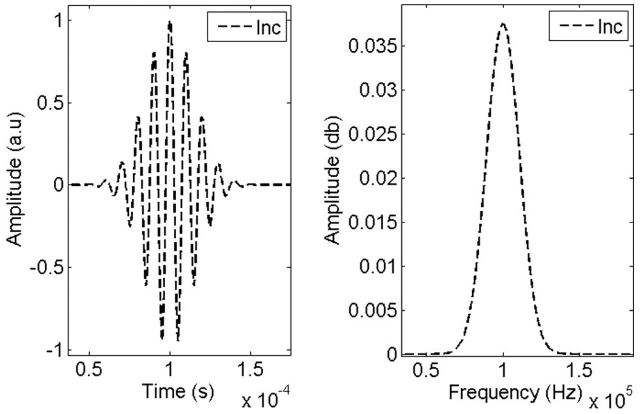

Fig. 2a. Simulated incident signal (dashed line) and the corresponding spectrum (solid line) with a central frequency of 100 kHz.

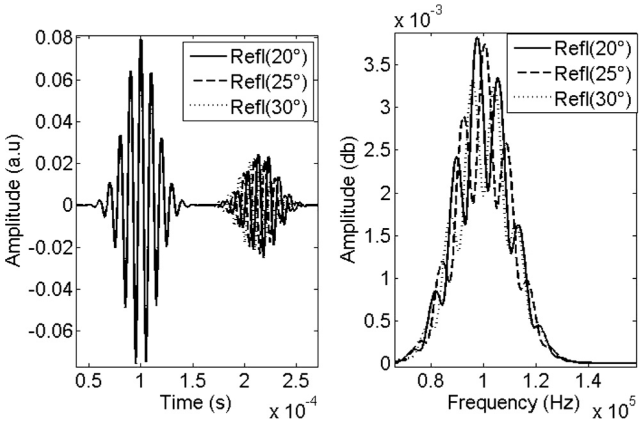

Fig. 2b. Simulated reflected signal (Refl) given by Eq. (8) using the expression (4) of the reflection coefficient and their spectrum for different oblique angles of incidence (20°,25° and 30°).

expression of the reflection coefficient from the surface of the porous medium. The expression obtained depends on the four physical parameters which are the porosity, the tortuosity, and the viscous and thermal characteristic lengths. The simulated reflected signal is calculated in the frequency domain by the product the spectrum of the incident signal with the reflection coefficient. In the time domain, the reflected wave is obtained by taking the inverse Fourier transform of the spectrum of the reflected signal. The sensitivity of each parameter is studied by showing their influence on the amplitude of the reflected wave from the surface of the porous sample for different oblique angles of incidence and in wide band of high frequency. The inverse problem is solved numerically using the last squares method. Four physical parameters are determined by minimizing between simulated and experimental reflected signals. The advantage of the proposed method over classical acoustic methods [6,17] is that all these parameters can be determined simultaneously. Moreover, no relationship is assumed between the two characteristic lengths.

2. Acoustical model

The porous material is a biphasic medium consisting of a solid part saturated with a fluid. Due to the coupling between the solid skeleton and the fluid, the propagation of acoustic waves in the material is well described by Biot's theory [3]. According to this theory; three waves propagate within the material: two compression waves, one related to the fluid phase and the other to the solid phase, and a shear wave in the solid phase. The porous medium is considered rigid [4,5,10,11,18–21] when the density or the stiffness of the solid phase is high which requires a large amount of energy to cause a displacement under acoustic excitation, in this cases the compression wave can be consider as propagating only in a fluid and the porous medium is considered as a fluid equivalent [1,2,4–6,18–21] with an effective density $\widetilde{\rho}$ and a bulk modulus $\widetilde{K}$(the tilde symbol ($\sim$) indicates that the associated variable is a complex value and depends on the frequency). In frequency domain, these loses are related by the two frequency response factors which are the dynamic tortuosity of the medium $\alpha(\omega)$ given by Johnson et al.[1] and the dynamic compressibility of the fluid included in the porous material $\beta(\omega)$ given by Allard [2,5] by the relations $\widetilde{\rho} = \rho_0\alpha(\omega)$ and $\widetilde{K} = K_a/\beta(\omega)$ where ρ_0 and K_a are the density and bulk modulus of the fluid in free space and ω is the pulsation frequency. The ultrasonic regime, also called high-frequency domain [5,8–11,18,19], corresponds to the frequency range such that the viscous skin thickness $\delta(\omega) = \sqrt{2\eta/\omega\rho_0}$ is much smaller than the radius of the pores $r\left(\frac{\delta}{r} \ll 1\right)$, wherein η is the fluid viscosity. In high-frequency approximation, the dynamic tortuosity and the dynamic compressibility of the medium are related to the three geometric parameters of the porous medium which are the tortuosity α_∞ initially introduced by Zwikker and Kosten [4], the viscous characteristic length Λ introduce by Johnson [1] and the thermal characteristic length Λ' introduce by Allard [2,5]. The relevant physical parameters of the model are involved in the classical Johnson-Champoux-Allard model (JCA) given by[2,5]:

$$\alpha(\omega) = \alpha_\infty\left(1 + \frac{\delta(\omega)}{\Lambda}\left(\frac{2}{j}\right)^{\frac{1}{2}}\right), \tag{1}$$