Transmission of Ultrasonic Waves Through Porous Layers of High Flow Resistivity Saturated by Air

Luc Kelders, Walter Lauriks, and Jean François Allard

Abstract—Transmission of ultrasonic waves through porous materials of high flow resistivity and porosity (in contact with air at both faces) is modelled and measured for an open-bubble foam at normal and oblique incidence. The importance of the airborne wave and the differences with the case of an elastic nonporous solid are demonstrated. A simple method to measure the shear modulus and the Poisson coefficient of the frame is suggested for similar materials.

I. INTRODUCTION

EARLY STUDIES, performed by Zwicker and Kosten [1], have shown that two compressional waves can propagate in a porous medium saturated by air. In [1], the concept of partial decoupling also is developed, which is a consequence of the large density of the porous frames, compared to the density of air. If the flow resistivity σ of the material is sufficiently small (σ is the ratio of the viscosity of air to the permeability of the frame), one of the two compressional waves, the airborne wave, mainly propagates in the air of the pore space, the frame being too heavy to move in a noticeable way in spite of the air-frame interaction. The second compressional wave, called the frameborne wave, propagates in the frame and in the air of the pores. This wave is very similar to the longitudinal wave in the frame set in vacuum, the air in the pore space is displaced by the frame vibrations without modifying them in a noticeable way. Let ρ_1 be the frame density and ω the angular frequency, a rough condition for the validity of this description, given in [1], is

$$\rho_1 \omega / \sigma > 1. \quad (1)$$

The presence of a shear frameborne wave was suggested by Biot [2] in a more complete and physical description. The concept of partial decoupling does not appear in the work by Biot [2] where the saturating fluid is not necessarily lighter than the frame. The two compressional waves are defined as the slow wave and the fast wave. The slow wave is strongly damped and has a velocity that tends to

zero with decreasing frequency. For air-saturated porous media, the compressional waves become the fast and the slow waves when frequency decreases sufficiently (due to the increasing influence of the viscous interaction compared to the inertial effects). A confirmation of the Biot model [2] was given by Plona [3] with the observation of the slow wave. In the present work, the Biot model [2] is the theoretical background for a description of sound transmission through porous layers and a method of measuring the rigidity coefficients of the frame.

At ultrasonic frequencies (100 kHz), for a frame density $\rho_1 = 20 \text{ kg/m}^3$, condition (1) is satisfied for flow resistivities as large as $10^7 \text{ Nm}^{-4}\text{s}$. For usual porous sound-absorbing materials, the flow resistivity is much smaller; the order of magnitude is $10^3 \text{ Nm}^{-4}\text{s}$. In this case, a plane wave in air impinging on a porous layer is related only to an airborne wave in the layer. Measurements of the transmission coefficient have been performed extensively [4]–[6] for these materials, related to the evaluation of the characteristic dimensions Λ and Λ' and the tortuosity of the frame. The case of high flow resistivities is more involved. A general modelling of sound transmission with both waves, performed previously in the context of the Biot theory [2], is used in Section II to predict the transmission coefficient of a very resistive layer at normal incidence. At oblique incidence the shear wave is present. The velocity of the compressional wave is noticeably larger than the velocity of the shear wave, as for ordinary elastic solids, and it is generally larger than the sound speed in free air for rigid, highly resistive materials. There is a range of angles of incidence θ in which the compressional frameborne wave is evanescent but not the shear wave. A modelling of sound transmission with the three waves is used to predict the transmission coefficient in this case in Section III. An illustration is given in Section IV in which predictions and measurements are compared for a plastic foam of high-flow resistivity at normal and oblique incidence.

II. EVALUATION OF TRANSMISSION AT NORMAL INCIDENCE WITH A SIMPLIFIED BIOT'S MODEL

The porosity h of the porous medium studied is very close to one, and the bulk modulus of the material of which the frame is made is much larger than the bulk modulus of the frame. The Biot parameters P , Q , and R can be

Manuscript received October 22, 1997; accepted May 5, 1998.

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written [2], [7]:

$$P = \frac{2N(\nu + 1)}{3(1 - 2\nu)} + \frac{4}{3}N, \quad (2)$$

$$Q = 0, \quad (3)$$

$$R = K_f. \quad (4)$$

In these expressions, K_f is the bulk modulus of air, N the shear modulus and ν the Poisson ratio of the frame. The Biot coefficients ρ_{11} , ρ_{22} , and ρ_a are given by:

$$\rho_{11} = \rho_1 + \rho_a, \quad (5)$$

$$\rho_{22} = \rho_f + \rho_a, \quad (6)$$

$$\rho_a = \rho_f(\alpha_\infty - 1), \quad (7)$$

where ρ_f is the density of air and α_∞ the tortuosity.

The simplified stress-strain relations in Biot's theory [2] with porosity h close to 1 for unidimensional displacements of air and frame in the z direction are:

$$\sigma_s = P e_z, \quad (8)$$

$$\sigma_a = R \varepsilon_z \quad (9)$$

where σ_s and σ_a are forces in the z direction acting on frame and air per unit area of material, e_z and ε_z the strain related to the frame and the air, respectively. The coupled equations for the compressional waves are:

$$\frac{\partial^2}{\partial z^2} P e_z = \frac{\partial^2}{\partial t^2} (\rho_{11} e_z - \rho_a \varepsilon_z) + b \frac{\partial}{\partial t} (e_z - \varepsilon_z), \quad (10)$$

$$\frac{\partial^2}{\partial z^2} R \varepsilon_z = \frac{\partial^2}{\partial t^2} (-\rho_a e_z + \rho_{22} \varepsilon_z) - b \frac{\partial}{\partial t} (e_z - \varepsilon_z). \quad (11)$$

In these equations, b is the viscous coupling term. The bulk modulus K_f and b in the present work are given by [8], [9]

$$b = \sigma \left(1 + 4j \frac{\alpha_\infty^2 \eta \rho_f \omega}{\sigma^2 \Lambda^2} \right)^{1/2}, \quad (12)$$

$$K_f = \gamma P_0 \left\{ \gamma - (\gamma - 1) \times \left[1 + \frac{8\eta}{j\Lambda'^2 Pr \omega \rho_f} \left(1 + j\rho_f \frac{\omega Pr \Lambda'^2}{16\eta} \right)^{1/2} \right]^{-1} \right\}^{-1}. \quad (13)$$

In these equations, P_0 is the static atmospheric pressure, γ the ratio of specific heats, Pr the Prandtl number, Λ and Λ' the characteristic dimensions.

Denoting by $\tilde{\rho}_{11}$, $\tilde{\rho}_{12}$, and $\tilde{\rho}_{22}$ the parameters:

$$\tilde{\rho}_{11} = \rho_{11} + \frac{b}{j\omega}, \quad (14)$$

$$\tilde{\rho}_{12} = -\rho_a - \frac{b}{j\omega}, \quad (15)$$

$$\tilde{\rho}_{22} = \rho_{22} + \frac{b}{j\omega}, \quad (16)$$

the wavenumbers k_1 and k_2 of the two compressional waves are given by [7]:

$$k_1^2 = \frac{\omega^2}{2PR} (P\tilde{\rho}_{22} + R\tilde{\rho}_{11} + \sqrt{\Delta}), \quad (17)$$

$$k_2^2 = \frac{\omega^2}{2PR} (P\tilde{\rho}_{22} + R\tilde{\rho}_{11} - \sqrt{\Delta}), \quad (18)$$

where Δ is given by

$$\Delta = (P\tilde{\rho}_{22} + R\tilde{\rho}_{11})^2 - 4PR(\tilde{\rho}_{11}\tilde{\rho}_{22} - \tilde{\rho}_{12}^2). \quad (19)$$

Choosing for $\sqrt{\Delta}$, the determinant with a positive real part, the wavenumber of the airborne wave (the frame-borne wave) is k_1 (k_2) for the material studied in Section III. The ratio ϕ_i , $i = 1, 2$, of the velocity v_a of the air to the velocity v_s of the frame indicates whether the wave propagates mainly in air or mainly in the solid frame. It is given by [7]:

$$\phi_i = (Pk_i^2 - \omega^2 \tilde{\rho}_{11}) / \omega^2 \tilde{\rho}_{12}, \quad i = 1, 2 \quad (20)$$

From (8) and (9), characteristic impedances Z_i^s for the frame and Z_i^a for air are:

$$Z_i^s = Pk_i / \omega, \quad (21)$$

$$Z_i^a = Rk_i / \omega \quad i = 1, 2 \quad (22)$$

A porous layer is presented in Fig. 1, in contact with air at both faces, insonified by a plane wave impinging on the front face at an angle of incidence θ . At $\theta = 0$, the acoustic field inside the layer consists of two compressional waves propagating from the front face to the rear face and in the opposite direction. Let v_a and v_s be the particle velocity of the frame and of air inside the layer. A transfer matrix $[\gamma]$ relates the quantities σ_s , σ_a , v_s , and v_a at A and B located at the front and the rear face, respectively, for the same value of x_1 :

$$\begin{bmatrix} \sigma_s^A \\ \sigma_a^A \\ v_s^A \\ v_a^A \end{bmatrix} = [\gamma] \begin{bmatrix} \sigma_s^B \\ \sigma_a^B \\ v_s^B \\ v_a^B \end{bmatrix}. \quad (23)$$

The matrix elements γ_{ij} are given in [10]. The pressure p^A in the air outside the porous layer (p^B at B) is related to σ_a^A and σ_s^A (σ_a^B and σ_s^B) by:

$$\sigma_a^A = -hp^A, \quad (24)$$

$$\sigma_s^A = -(1 - h)p^A, \quad (25)$$

$$\sigma_a^B = -hp^B, \quad (26)$$

$$\sigma_s^B = -(1 - h)p^B. \quad (27)$$

The velocities of air out of the layer v^A and v^B are related to v_s^A , v_a^A , v_s^B , v_a^B by:

$$v^A = (1 - h)v_s^A + hv_a^A, \quad (28)$$

$$v^B = (1 - h)v_s^B + hv_a^B. \quad (29)$$

Fig. 1. Experimental set up. (a)–(c): recording of the reference signal in air. (d)–(f): recording of the transmitted signal. Typical time signals (b) and (e) and their Fourier transforms (c) and (f) are shown.

For a porosity close to one, (24)–(29) can be replaced by:

$$\sigma_a^A = -p^A, \quad (30)$$

$$\sigma_s^A = 0, \quad (31)$$

$$\sigma_a^B = -p^B, \quad (32)$$

$$\sigma_s^B = 0, \quad (33)$$

$$v^A = v_a^A, \quad (34)$$

$$v^B = v_a^B. \quad (35)$$

From (23), (30) to (35), it is possible to relate p^A , v^A , and p^B , v^B by:

$$\begin{bmatrix} p^A \\ v^A \end{bmatrix} = [G] \begin{bmatrix} p^B \\ v^B \end{bmatrix}, \quad (36)$$

where the matrix elements G_{ij} are given by:

$$G_{11} = (\gamma_{22}\gamma_{13} - \gamma_{12}\gamma_{23})/\gamma_{13}, \quad (37)$$

$$G_{12} = (\gamma_{24}\gamma_{13} - \gamma_{14}\gamma_{23})/\gamma_{13}, \quad (38)$$

$$G_{21} = (\gamma_{42}\gamma_{13} - \gamma_{12}\gamma_{43})/\gamma_{13}, \quad (39)$$

$$G_{22} = (\gamma_{44}\gamma_{13} - \gamma_{14}\gamma_{43})/\gamma_{13}. \quad (40)$$

The transmission coefficient T is given by:

$$T = 2Z_c^{-1} / (G_{21} + Z_c^{-1}(G_{11} + G_{22}) + G_{12}Z_c^{-2}), \quad (41)$$

where Z_c is the characteristic impedance of free air.

For materials having a large flow resistivity, $\sin k_1\lambda$ and $\cos k_1\lambda$, λ being the thickness of the layer, are very large due to the noticeable damping of the airborne wave. Equations (37)–(40) can be replaced by simpler expressions:

$$G_{11} = \cos k_2\lambda - j \frac{Z_2^s \phi_1 \sin k_2\lambda}{Z_1^s \phi_2}, \quad (42)$$

$$G_{22} = G_{11}, \quad (43)$$

$$G_{12} = -j \frac{D \sin k_2\lambda}{Z_1^s \phi_2}, \quad (44)$$

$$G_{21} = \frac{-j}{D Z_1^s \phi_2} [2j Z_1^s Z_2^s \phi_1 \phi_2 \cos k_2\lambda + \sin k_2\lambda (\phi_1^2 Z_2^{s2} + \phi_2^2 Z_1^{s2})], \quad (45)$$

where D is given by:

$$D = Z_2^s Z_1^a \phi_1 - Z_1^s Z_2^a \phi_2. \quad (46)$$

The condition for reciprocity ($\det[G] = 1$) and symmetry ($G_{11} = G_{22}$) are fulfilled. Sound transmission is now due to the frameborne wave. It may be noticed that the matrix defined by (42)–(45) describes the transmission related to a compressional wave with a wavenumber k_2 and a characteristic impedance Z_2^a in an equivalent elastic fluid if $Z_2^s \phi_1 / (Z_1^s \phi_2)$ is equal to zero. The airborne wave, for materials having a sufficiently large flow resistivity, is present with a finite amplitude at both faces (propagating toward the other face) [to fulfill conditions (31) and (33) ($\sigma_s^A = \sigma_s^B = 0$)] and disappears at a small distance from the faces. Sound propagation is due to the frameborne wave. The unphysical condition $Z_2^s \phi_1 / (Z_1^s \phi_2) = 0$ is related to an airborne wave that has no detectable effect in free air close to the layer. The only detectable effect of the porous layer then is the presence of the air-component of the frameborne wave with the characteristic impedance Z_2^a . It may be noticed that at the limit of very large flow resistivities, in the context of the Biot theory [2], the matrix $[G]$ cannot be simplified by using the condition $Z_2^s \phi_1 / (Z_1^s \phi_2) = 0$. The airborne wave and the frameborne wave become the slow wave, and the fast wave, respectively, described in [2]. The ratios ϕ_1 and ϕ_2 tend to the limits [11]:

$$\phi_1 = -\frac{P}{R}, \quad (47)$$

$$\phi_2 = 1 \quad (48)$$

and k_1^2 and k_2^2 to [11]:

$$k_1^2 = \frac{\omega^2}{P\tilde{R}} (P\tilde{\rho}_{22} + R\tilde{\rho}_{11}), \quad (49)$$

$$k_2^2 = \omega^2 \frac{\rho_0 + \rho_1}{P + R}. \quad (50)$$

The squared wavenumber k_1^2 can be rewritten:

$$k_1^2 = -j \frac{\omega \sigma}{PR} (P + R), \quad (51)$$

and the ratio k_2^2/k_1^2 tend to zero like ω/σ .

The ratio $Z_2^s \phi_1 / (Z_1^s \phi_2)$ is given by:

$$Z_2^s \phi_1 / (Z_1^s \phi_2) = -\frac{P}{(P + R)R} \left[j \frac{\omega(\rho_0 + \rho_1)(PR)}{\sigma} \right]^{1/2}, \quad (52)$$

and tends to zero, but simultaneously in D , $Z_1^a/Z_2^a = k_1/k_2$ tends to infinity, and both terms $Z_2^s Z_1^a \phi_1$ and $Z_1^s Z_2^a \phi_2$ have the same order of magnitude. The absence of simplifications is related to the fact that, in spite of its large damping, the slow wave contributes to the boundary conditions at the contact surfaces of the porous layer with air. For high flow resistivities [even if the unphysical condition $Z_2^s \phi_1 / (Z_1^s \phi_2) = 0$ were fulfilled], the porous material does not behave like a simple equivalent monophasic material with a density $\rho_0 + \rho_1$ and a rigidity coefficient for the longitudinal wave $P + R$. This is due to the boundary conditions (30)–(35). It may be shown that an impervious and massless screen in contact with both faces modifies these conditions so that the layer appears (for the surrounding semi-infinite air layers) exactly as the equivalent monophasic material.

III. TRANSMISSION AT OBLIQUE INCIDENCE

The description is restricted to the case in which the compressional wave is evanescent. The mathematical formulation is simpler, and measurements can be easily interpreted. The wavenumber k_3 and the ratio ϕ_3 for the shear wave are given, respectively, by:

$$\phi_3 = -\tilde{\rho}_{12}/\tilde{\rho}_{22} \quad (53)$$

$$k_3^2 = \omega^2(\tilde{\rho}_{11}\tilde{\rho}_{22} - \tilde{\rho}_{12}^2)/(\tilde{\rho}_{22}N). \quad (54)$$

Let $k_{1,i}$ and $k_{3,i}$, $i = 1, 3$, be the x_1 and the x_3 components of the three waves. Let A_1^0 and A_1^λ be the amplitudes of the velocity potentials of the frame for the airborne wave at A and B, and A_2^0 and A_2^λ the same quantities for the compressional frameborne wave. Let A_3 and A_3' be the amplitudes for the shear wave at face A propagating toward B and in the opposite direction. The two compressional waves are present at each face of the layer and disappear at a small distance from the faces. Sound transmission is performed by the shear wave. The stress components of the frame can

be obtained from the more general (7.25)–(7.26) of [7]:

$$\sigma_t^A = 0 = N \left[-2k_t (k_{13}A_1^0 + k_{23}A_2^0) + (k_{33}^2 - k_t^2) (A_3 + A_3') \right], \quad (55)$$

$$\sigma_t^B = 0 = N \left[2k_t (k_{13}A_1^\lambda + k_{23}A_2^\lambda) + (k_{33}^2 - k_t^2) [(A_3 + A_3') \cos k_{33}\lambda - j(A_3 - A_3') \sin k_{33}\lambda] \right] \quad (56)$$

$$\sigma_s^A = 0 = -B_1A_1^0 - B_2A_2^0 - 2Nk_t k_{33} (A_3 - A_3'), \quad (57)$$

$$\sigma_s^B = 0 = -B_1A_1^\lambda - B_2A_2^\lambda - 2jNk_t k_{33} (A_3 + A_3') \sin k_{33}\lambda - 2Nk_t k_{33} (A_3 - A_3') \cos k_{33}\lambda. \quad (58)$$

In these equations k_t is the x_1 component of the wavenumber vector of all the waves, and B_i $i = 1, 2$ is given by:

$$B_i = Pk_i^2 - 2Nk_t^2 \quad i = 1, 2. \quad (59)$$

Let us denote by $X(\lambda)$ and $Y(\lambda)$ the parameters dependent on λ given by:

$$X(\lambda) = \frac{k_{33}^2 - k_t^2}{2k_t} [(A_3 + A_3') \cos k_{13}\lambda - (A_3 - A_3') j \sin k_{13}\lambda] / (k_{13}B_2 - k_{23}B_1), \quad (60)$$

$$Y(\lambda) = 2Nk_t k_{33} [(A_3 - A_3') \cos k_{13}\lambda - (A_3 - A_3') j \sin k_{13}\lambda] / (k_{13}B_2 - k_{23}B_1). \quad (61)$$

The amplitudes A_1^0 , A_2^0 , A_1^λ , and A_2^λ are given by:

$$A_1^0 = B_2X(0) + k_{23}Y(0), \quad (62)$$

$$A_2^0 = -B_1X(0) - k_{13}Y(0), \quad (63)$$

$$A_1^\lambda = -B_2X(\lambda) + k_{23}Y(\lambda), \quad (64)$$

$$A_2^\lambda = B_1X(\lambda) - k_{13}Y(\lambda). \quad (65)$$

Using (7.17) and (7.27) of [7] [a factor j must be added before $(A_i - A_i')$ in (7.27)], pressure and air velocity at both faces can be written:

$$-p^A = -D_1A_1^0 - D_2A_2^0, \quad (66)$$

$$-p^B = -D_1A_1^\lambda - D_2A_2^\lambda, \quad (67)$$

$$v_a^A = j\omega [-jk_{13}\phi_1A_1^0 - jk_{23}\phi_2A_2^0 - jk_t\phi_3(A_3 + A_3')], \quad (68)$$

$$v_a^B = j\omega [jk_{13}\phi_1A_1^\lambda + jk_{23}\phi_2A_2^\lambda - jk_t\mu_3(A_3 + A_3') \cos k_{33}\lambda - k_t\mu_3(A_3 - A_3') \sin k_{33}\lambda]. \quad (69)$$

In these equations, D_1 and D_2 are given by:

$$D_i = R\phi_i k_i^2 \quad i = 1, 2. \quad (70)$$

Substituting (62)–(65) for A_1^0 , A_2^0 , A_1^λ , and A_2^λ in (66)–(69) provides two matrix equations:

$$\begin{pmatrix} p^A \\ v_a^A \end{pmatrix} = [H] \begin{pmatrix} A_3 - A_3' \\ A_3 + A_3' \end{pmatrix}, \quad \begin{pmatrix} p^B \\ v_a^B \end{pmatrix} = [H'] \begin{pmatrix} A_3 - A_3' \\ A_3 + A_3' \end{pmatrix}, \quad (71)$$

which relate $\begin{pmatrix} p^A \\ v_a^A \end{pmatrix}$ and $\begin{pmatrix} p^B \\ v_a^B \end{pmatrix}$ by:

$$\begin{pmatrix} p^A \\ v_a^A \end{pmatrix} = [H''] \begin{pmatrix} p^B \\ v_a^B \end{pmatrix}, \quad (72)$$

where

$$[H''] = [H][H']^{-1}. \quad (73)$$

The transmission coefficient T' is given by:

$$T' = 2 \cos \theta Z_c^{-1} / (H_{21}'' + \cos \theta Z_c^{-1} (H_{11}'' + H_{22}'') + H_{12}'' \cos^2 \theta Z_c^{-2}). \quad (74)$$

IV. EXPERIMENTAL MEASUREMENT

The experimental procedure is shown in Fig. 1. A Panametrics V3052 piezoelectric transducer is used as a source and a high frequency B&K 4138 microphone for the detection. The ratio S of the Fourier transform of the signal after transmission through the layer [Fig. 1(f)] and the Fourier transform of the reference signal [when the layer is removed, Fig. 1(c)] is related to T by:

$$T = S \exp(-jk_0 \lambda \cos \theta), \quad (75)$$

where k_0 is the wavenumber in the free air. The length $\lambda \cos \theta$ is the distance between the equiphase planes in air P_A and P_B (See Fig. 2).

Predicted and measured transmission loss $\tau = 1/T$ for a layer of plastic foam of thickness $\lambda = 2$ cm is presented in Fig. 3 at normal incidence and Fig. 4 at $\theta = \pi/4$. The sample is a nonreticulated rigid polyurethane foam with small perforations in the cell membranes. The order of magnitude of the flow resistivity is $5 \times 10^6 \text{ Nm}^{-4}\text{s}$, the open porosity h is equal to 0.98 and the density ρ_1 is equal to 24 kg/m^3 . The parameters α_∞ , Λ , and Λ' are not measurable by sound transmission due to the damping of the airborne wave. The complex parameter P can be evaluated from the transmission measurement at normal incidence, the real part of P being related to the periodicity of the maxima and the minima of $|T|$, independently on σ , Λ , and Λ' in large range of variation of these parameters, and the imaginary part is related to the amplitude variations with a weak dependence on the other parameters. The adjusted value for P is $(6.3 + j0.42) \times 10^6 \text{ Pascal}$. The other parameters used for the predictions are $\alpha_\infty = 1.5$, $\sigma = 5 \times 10^6 \text{ Nm}^{-4}\text{s}$, $\Lambda = \Lambda' = 10^{-5} \text{ m}$, $h = 1$.

At $\theta = \pi/4$, the compressional frameborne wave is evanescent and the model of Section III can be used.

The transmission is performed by the shear wave, and the periodicity of τ mainly depends on the real part of N . The adjusted value for N is $(2.1 + j0.14) \times 10^6 \text{ Pascal}$. The Poisson's ratio ν is equal to 0.25. The airborne wave, in spite of its large damping, cannot be neglected in the boundary conditions. The shear wave does not contribute to the pressure in the porous material. A simple calculation

Fig. 2. A porous layer in contact with air at both faces A and B. The equiphase planes related to A, B and the receiver R are P_A , P_B and P_R . The distance between P_A and P_B is d .

Fig. 3. Transmission loss at normal incidence measurement —, prediction ---.

Fig. 4. Transmission loss at $\theta = \pi/4$ measurement —, prediction ---.

shows that the airborne wave contributes to the pressure p_B with the same order of magnitude as the compressional airborne wave.

V. CONCLUSION

Sound transmission through porous media of high flow resistivity can be described by the same formalism, the Biot theory, as for media of low flow resistivity, in spite of the fact that, in the first case, sound transmission is mainly due to the frameborne waves, and to the airborne wave in the second case. Sound transmission measurements in the first case provide a method of evaluation of the velocity of the frameborne waves, and the related rigidity coefficients, with no mechanical contact between transducers and the porous layer. This method presents the following advantages: it avoids the modifications of the medium due to static charges, nonlinear effects due to the amplitude of excitation, and imprecise boundary conditions at the contact surface with the transducers.

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