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Recovery of airflow resistivity of poroelastic beams submitted to transient mechanical stress

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The airflow resistivities of air-saturated poroelastic slender beams submitted to transient mechanical stress are recovered using fluid and solid borne compressional mode phase velocity expressions drawn from a modified Biot theory. A point where the two dilatational modes intersect and their phase velocities equal is first sought. This point also corresponds to the Biot transitional frequency indicating the frequency at which the solid and the pore fluid start disassociating due to the weakening of the viscous forces by the thinning of the viscous boundary layer in the pores. A bilinear time–frequency (TF) distribution is used to represent on the time–frequency plane, the captured transient mechanical stress waves from which the point of intersection/separation of the two modes is located. The projection of the Eigenfrequencies obtained from a simple 3D finite element modeling of the thin poroelastic beam, on a (TF) diagram, facilitates the identification of the modes. The transition frequencies for the poroelastic beams thus retrieved are verified through the use of variable frequency, single cycle sine wave bursts. The anisotropy of the foams are also revealed by analyzing the transient responses of the poroelastic beam specimens cut from the same panel but in two perpendicular directions in orientation to each other.

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1. Introduction

Elastic wave interaction with poroelastic materials (bone, foam, rocks, soil etc.) is complicated and the understanding of the underlying mechanisms can ultimately help in deriving better mathematical wave propagation models to assist in the interpretation of signals pertaining to guided wave modes and consequently to their characterization.

Most macroporous polymers (plastic foams) are used for noise and energy control applications and knowledge of the manner in which the energy of sound waves is dissipated (through viscous and thermal effects and structural damping) with respect to the intrinsic acoustic properties is important for the design of sound packages. These packages are often made up of a combination of porous media that are two phase materials: solid and fluid.

Acoustic modeling and characterization of the loss phenomena in the low frequency regime for porous materials are still challenging. Airflow resistivity (σ) is one of the important parameters characterizing the capacity of noise absorption of sound packages in the low frequency regime. It is a measure that indicates how absorptive or how transmissive a porous or fibrous material is by evaluating the quantity of air that can pass through the material at a given volumetric flow rate.

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Measurements of the static airflow resistivity can be made directly [1–3] using a device in accordance with the ISO standard 9053 [4]. Alternative methods employ acoustic waves in ducts [5,6].

The popular semi-empirical single parameter Delany and Bazley model [7] linking σ to the surface impedance, has some shortcomings [8] i.e. not accurate at low frequencies [3,9]. Moreover the other methods employing acoustic waves consider the skeleton (frame) motionless (rigid) in the absence of mechanical excitation and the waves inside the porous material to propagate only inside the fluid phase [9–13]. The porous medium is then considered as an equivalent fluid characterized by an equivalent dynamic density $\tilde{\rho}_e$ and a dynamic bulk modulus $\tilde{K}_e$ both dependent on frequency, with the former accounting for the viscous losses, and latter the dynamic bulk compression modulus for the thermal losses. At low frequencies, in the poroelastic case, structural modes that increase the absorption coefficient are excited [14]. In this study the airflow resistivity is recovered by employing low frequency transient mechanical stress propagation method using a model that takes into account both the motion of the skeleton and the saturating fluid and the Biot transitional frequency [15–18].

The choice of the geometry of a sample employed for the characterization of a poroelastic media using elasto-acoustic waves is important as it partly determines the complexity of the mathematical interaction model for the inverse problem. The simplest geometry, which is also the one employed herein, that appeals to one dimensional (1D) elastic wave propagation modeling is the thin beam. It can be of different uniform cross-section geometries. The most common ones being the circular and rectangular forms. The energy of the different waves propagating in the thin beam structure is confined within its boundary such that it behaves like a waveguide. Characterization of such a sample using elasto-acoustic wave propagation is often complicated by waveguide and material dispersion.

Elasto-acoustic wave dispersion occurs when a wave propagating in a medium becomes frequency-dependent so that its velocity is no longer uniquely defined. An important temporal effect of dispersion is pulse-broadening or deformation which increases with the transit time for the dispersive and absorptive media. This makes accurate time-domain velocity measurement which becomes an issue because velocity is considered as a characteristic property parameter e.g. the speed of sound (SOS) is an indirect measurement of bone strength [19–22].

The method employed to study dispersion is based on the analysis of the time–frequency decomposition of captured, transient mechanical stresses and the representation of vibration spectroscopy data acquired from experiment on the time–frequency plane. A modified Biot theory [15,16] in which the thermal and viscous dissipations are taken into account by frequency dependent expressions for the compressibility and density, respectively, is employed to calculate the phase velocities of the three wave modes which are then plotted in a time–frequency plane. Their representation helps in the understanding of the different patterns resulting from the decomposition of the captured response consequent of the applied transient mechanical stress on the poroelastic beam waveguide.

The dispersion of extensional waves in fluid-saturated porous cylinders of infinite length has been studied theoretically by analyzing generalized Pochhammer equations derived using Biot's theory [23]. It was found that the dispersion of the fast extensional wave does not differ much qualitatively from the dispersion expected for the extensional wave in an isotropic elastic beam [24]. Consequently the time–frequency diagrams are plotted using eigenfrequencies from 3D finite element modeling (FEM) of the poroelastic beam considered as an equivalent elastic solid [25]. This provides a useful aide for the identification of some modes on the complicated time–frequency diagram.

1.1. The wave propagation equations in poroelastic media

The equations of motion for a fluid-saturated poroelastic media (two phase media) were formulated by Biot [15,16]. This motion is described by the macroscopic displacement of the solid and fluid phases represented by the vectors $\mathbf{u}$ and $\mathbf{U}$ respectively. The harmonic equation of motion can be written in the form

$$P\nabla(\nabla\cdot\mathbf{u}) - N\nabla\times(\nabla\times\mathbf{u}) + Q\nabla(\nabla\cdot\mathbf{U}) + \omega^2(\tilde{\rho}_{11}\mathbf{u} + \tilde{\rho}_{12}\mathbf{U}) = 0,$$

$$Q\nabla(\nabla\cdot\mathbf{u}) + R\nabla(\nabla\cdot\mathbf{U}) + \omega^2(\tilde{\rho}_{12}\mathbf{u} + \tilde{\rho}_{22}\mathbf{U}) = 0, \tag{1}$$

where ω is the angular frequency, P, Q, R are generalized elastic constants which are related, via Gedanken experiments, to other measurable quantities, namely ϕ, K_f (bulk modulus of the fluid), K_s (bulk modulus of the elastic solid), K_b (bulk modulus of the porous skeletal frame) and N (the shear modulus of the frame in vacuum).

The equations which explicitly relate P, Q and R to ϕ, K_f, K_s, K_b and N are given by [26]

$$P = \frac{(1-\phi)(1-\phi-K_b/K_s)K_s + \phi(K_s/K_f)K_b}{1-\phi-K_b/K_s+\phi K_s/K_f} + \frac{4}{3}N,$$

$$Q = \frac{(1-\phi-K_b/K_s)\phi K_s}{1-\phi-K_b/K_s+\phi K_s/K_f},$$

$$R = \frac{\phi^2 K_s}{1-\phi-K_b/K_s+\phi K_s/K_f},$$

in which the bulk modulus of the frame can be evaluated from the relation [26], $K_b = 2N(\nu_b+1)/[3(1-2\nu_b)]$ (ν_b is the Poisson ratio of the frame).

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