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Ultrasonic contact pulse transmission for elastic wave velocity and stiffness determination: Influence of specimen geometry and porosity ☆

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ABSTRACT

Elasticity determination by means of ultrasonic pulse transmission requires experimental realization of non-dispersive, i.e. frequency-independent, wave propagation, be it in form of bulk waves propagating in an (approximately) infinite medium, or of extensional waves propagating through a 1D bar system. While it is conceptually known that wavelengths need to tend towards zero (as compared to the specimen dimensions perpendicular to the pulse propagation direction) in the 3D case, and towards infinity in the 1D case, we here report on a new systematic experimental assessment of the influence of the sample geometry on wave type: tests on solid isotropic aluminum samples reveal that the extensional (or bar) wave propagation mode requires transmission of truly slender samples (required slenderness ratio of 20 or larger for wavelengths equal to the wave travel distance; this minimum slenderness ratio is increasing with increasing travel distance-over-wavelength ratio). After a transition zone with dispersive wave propagation, non-dispersive bulk waves are detected once the slenderness ratio is reduced to 5 or lower (at wavelengths equal to the wave travel distance; this maximum slenderness ratio is increasing with increasing travel distance-over-wavelength ratio). On the other hand, it is conceptually known from continuum mechanics that the wavelength needs to be larger than the investigated material volume or representative volume element (RVE), as to reveal the material's elastic properties, while corresponding quantitative data are rare. As a remedy, we here report on new experiments on transversely isotropic, porous aluminum samples, which reveal that minimum pore dimension-over-wavelength ratios of 1 and 10, respectively, relate to detection of normal and shear stiffnesses, respectively, of the solid material between the pores, while these ratios need to be smaller than 0.01 and 0.1, as to detect the normal and shear stiffnesses of the overall porous materials. The latter can be quantified through various homogenization techniques.

1. Introduction

The design of engineering structures is more and more governed by the development of new construction materials, whose characteristics are not known through long periods of experience, but result from appropriate, comprehensive experimental investigations. Hence, the portfolio of experimental techniques is ever increasing, and the reliability and limitations of such techniques needs to be carefully scrutinized. In the present contribution, we concentrate on a method which is particularly appropriate for elasticity determination, namely the ultrasonic (contact) pulse technique. This technique was originally developed for the detection of flaws in metals [25,50], and thereafter applied to a wide range of materials, including single crystals [37,50], polycrystalline materials [32,58], polymers [39,28], metals and metal alloys [57,53], composite materials [59,19,48], geomaterials [33,14,40], biological materials such as bone [2] and wood [13,44], as well as biomaterials such as porous titanium and glass-ceramic scaffolds [45].

In the present contribution, we leave aside Rayleigh surface waves, Lamb waves, and guided waves (see e.g. [47,82,76] for detailed explanations), we are also not dealing with plastic waves, shock waves, or viscoelastic waves [14], but our focus lies on elastic waves used in the framework of the so-called transmission through technique. There, an acoustic pulse is introduced at one end of a material sample, and it is measured how long it takes to detect this pulse, after having travelled through the sample, at the opposite end of the sample. The traveling pulse is called wave, and the velocity of the latter is related to the elastic properties of the material. However, there are two limiting cases of such waves: (i) bulk waves, related to propagation of pulses in infinite media and (ii) extensional waves propagating along 'one-dimensional media', i.e. through samples being of very elongated shape,

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commonly called bars. While numerous studies [36,62,75,82,30,31] were devoted to the dispersion (i.e. the frequency dependence) of waves in bars fulfilling Pochhammer's boundary conditions [73,15], the frequency-dependent transition of pulse signals, from bulk wave propagation to extensional wave propagation has been quite rarely studied [83,2]. For these limit cases, compact and therefore highly practical mathematical formulae exist. Hence, the question arises under which conditions these limit cases can be experimentally observed in real (i.e. neither infinite 3D, nor perfectly 1D) material samples. It is known from Kolsky [46,47], and considered in subsequent experimental activities [2,45], that the transition from bar to bulk waves starts once the (decreasing) wave length attains the lineal dimension of the cross section of the bar. However, the effect of the bar's slenderness on the type of wave transmitting it, is comparatively unknown, and this is the first main issue to be discussed in the present paper.

Both bulk and extensional waves relate to the long-wavelength-limit, referring to wavelengths being considerably larger than the characteristic length of the material volumes (also called representative volume elements [92]) building up the medium through which the waves travel. If the wavelength attains the size of the material volume, the wave starts to 'feel' the material microstructure, e.g. they may be scattered at inhomogeneities (e.g. inclusions) inside the material volume. The transition from the long-wavelength-limit to waves scattered by microstructural elements has been the topic of various theoretical investigations, be it in the framework of random homogenization theory [60,38,8,78,80,91,90,86] or of periodic homogenization technique [26,49,85,10,11,18,84,65,66,89,27,52,72]. We here do not concentrate so much on this transition, but rather focus on the experimental revelation of two limit cases: the aforementioned long-wavelength-limit (how large needs a wave to be in order to feel the 'homogenized medium' rather than microstructural details?), and also the 'short-wavelength-limit' (how small needs a wave to be to 'feel' the material components themselves, rather than their microstructural interaction?). The short-wavelength-limit was beyond the aforementioned theoretical investigations, relating to the question: how short needs a wave to be in order to find an unscattered path between the microstructural inhomogeneities? Obviously, the answers depend on the type of chosen microstructures. We here choose an extreme case: zero-stiffness, cylindrical pore inclusions.

Accordingly, the paper is organized as follows: after recalling some foundations of plane wave propagation theory (Section 2), we present the ultrasonic measurement system used for the present study (Section 3) and the investigated specimens (Section 4), together with a precision check of our measurement system (Section 5). On this basis, we study the transition from bulk to extensional waves (Section 6), and from the long-wavelength-limit to the short-wavelength-limit (Section 7), both from a dimensional analysis viewpoint. After discussing the experimental results from a micromechanics viewpoint (Section 8), we conclude the paper in Section 9 by giving operational rules for reliable ultrasonic pulse transmission protocols.

2. Wave propagation in 3D and 1D linear elastic solids – theoretical basics

We focus on wave propagation in continua – where the basic property of a continuum solid is that its deformations can be described through representative volume elements (RVEs) 'labeled' on the continuum and staying neighbors during deformation [79]. The characteristic lengths ℓ of such RVEs need to be much smaller than those of the body made up of the RVEs or than the excitation lengths of that body [such as wavelengths λ, see Eq. (7)] – then use of differential calculus is admissible; and the RVE-length ℓ needs to be much larger than the microheterogeneities with characterisitic length d within the RVE (e.g. the void diameter in Fig. 1) – then material properties such as stiffness can be introduced. Mathematically, this is expressed by means of the separation-of-scales requirement [92],

$$d \ll \ell \ll \lambda. \tag{1}$$

When considering an infinitely extended 3D medium, the aforementioned stiffness is quantified in terms of the elasticity tensor $\mathbb{C}$, relating (small) strains to stresses. Based on earlier work of Christoffel [16,17], Love [55] was the first to mathematically capture the propagation of elastic waves in infinite three dimensional solids, be they isotropic or anisotropic. In the case of transversely isotropic materials, to which we restrict ourselves in this paper, the independent components of the stiffness tensor are related to velocities of waves traveling in the principal directions of the material, namely in the axial direction (labeled 3), and all directions perpendicular to this axial direction (making up the transverse plane), including directions 1 and 2, being also orthogonal to each other. To fully characterize the aforementioned waves, called bulk waves, also their polarization direction (i.e. the direction of the movement of the material particles or RVEs) needs to be known; and again, we restrict the polarization directions to the principal material directions, and label wave velocities $v_{i,j}$ with two indices, the first one (i) being related to the wave direction, and the second one (j) to the polarization direction. In case of longitudinal waves, the polarization directions coincide with the propagation directions, and corresponding wave velocities are related to normal stiffness tensor components, see e.g. [24,14,44] for details,

$$v_{1,1} = v_{2,2} = \sqrt{\frac{C_{1111}}{\rho}}, \quad v_{3,3} = \sqrt{\frac{C_{3333}}{\rho}}, \tag{2}$$

with ρ as the mass density of the considered material. In case of transverse waves, the polarization direction is perpendicular to the propagation direction, and corresponding wave velocities are related to shear stiffness tensor components, see e.g. [24,14,44] for details,

$$v_{1,2} = v_{2,1} = \sqrt{\frac{C_{1212}}{\rho}}, \quad v_{1,3} = v_{3,1} = v_{2,3} = v_{3,2} = \sqrt{\frac{C_{1313}}{\rho}}. \tag{3}$$

In case of isotropy, wave propagation velocities are independent of the propagation direction, and in all directions, the wave velocities follow from specification of (2) and (3) for $C_{3333} = C_{1111}$ and $C_{1313} = C_{1212}$ so that we have

$$v_L = \sqrt{\frac{C_{1111}}{\rho}} \quad \text{and} \quad v_T = \sqrt{\frac{C_{1212}}{\rho}}, \tag{4}$$

with v_L and v_T as the velocities of longitudinal and transverse (or shear) waves in isotropic media. Since isotropic solids are completely described by two elastic constant, e.g. C_{1111} and C_{1212} (the shear modulus G is equal to the shear stiffness component, i.e. $G = C_{1212}$), the two velocities v_L and v_T can also be used to determine two engineering elastic constants, e.g. Young's modulus and Poisson's ratio, in the form

$$E = \rho\,\frac{v_T^2(3v_L^2 - 4v_T^2)}{v_L^2 - v_T^2} \quad \text{and} \quad \nu = \frac{v_L^2/2 - v_T^2}{v_L^2 - v_T^2}. \tag{5}$$

When considering 1D media, i.e. bars characterized by a one-dimensional state of normal stress, there is only one (extensional or bar) wave propagating through the considered bar, with its wave velocity being related to the Young's modulus E of the material, see [46] for details,

$$v_E = \sqrt{\frac{E}{\rho}}. \tag{6}$$