Applied Acoustics 88 (2015) 6–11

Contents lists available at ScienceDirect

Applied Acoustics

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

Ultrasonic wave propagation through porous ceramics at different angles of propagation

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ARTICLE INFO

Article history:
Received 3 January 2014
Received in revised form 19 May 2014
Accepted 24 July 2014
Available online 15 August 2014

Keywords:
Ultrasound
Wave propagation
Ceramics
Biot theory

ABSTRACT

The anisotropic pore structure and elasticity of cancellous bone cause wave speeds and attenuation in cancellous bone to vary with angle. Comparisons between predictions of a Biot–Allard model allowing for angle-dependent elasticity and angle-and-porosity dependent tortuosity and transmission data obtained on water-saturated replica bones at normal and oblique incidence are extended to water saturated porous rigid ceramic at different angles of propagation. It is found that predictions of the variation of transmitted waveforms with angle through porous ceramic are in reasonable agreement with data.

1. Introduction

Bone essentially has two types of structure, both having the same mineralized collagen composition. Cortical bone may generally be considered to be solid; cancellous bone consists of a complex open-celled porous network of rod- and plate-shaped elements termed trabeculae. Osteoporosis is a bone disease caused by hormonal and biochemical changes. Osteoporosis leads to nearly 9 million fractures annually worldwide [1], and over 300,000 patients present with fragility fractures to hospitals in the UK each year [2]. Direct medical costs from fragility fractures to the UK healthcare economy were estimated at £1.8 billion in 2000, with the potential to increase to £2.2 billion by 2025, and with most of these costs relating to hip fracture care [3].

To improve the prediction of fracture risk by ultrasound it is important to understand the propagation of acoustic waves through porous rigid materials. Biot theory has been used extensively to describe the wave propagation in cancellous bone [4–12]. It was specifically developed to describe acoustic wave propagation in fluid-saturated porous elastic media [13,14]. Biot theory predicts two compressional waves (fast and slow waves), when the waves propagating through the solid frame of bone and marrow are in-phase and out-of-phase respectively, and a shear wave. It allows for an arbitrary microstructure, with separate motions considered for the solid elastic framework (bone) and the interspersed fluid (marrow), induced by the ultrasonic wave, and also includes energy loss due to viscous friction between solid (bone) and fluid (marrow).

The anisotropic pore structure and elasticity of cancellous bone cause wave speeds and attenuation in cancellous bone to vary with angle [15]. Previous work on the influence of anisotropic pore structure and elasticity in cancellous bone has been extended by developing an anisotropic Biot–Allard model allowing for angle-dependent elasticity, and angle-and-porosity dependent tortuosity [15]. The extreme angle dependence of tortuosity corresponding to the parallel plate microstructure used by Hughes et al. [4] has been replaced by angle-and-porosity dependent tortuosity values based on data for slow wave transmission through air-filled stereolithography (STL) bone replicas [16]. It has been suggested that the anisotropic Biot–Allard model could be used to give further insight into the factors that have the most important influence on the angle dependency of wave speeds and attenuation in cancellous bone. Nevertheless the applicability of Biot-based theories to ultrasonic propagation in bone remains in question given the expected role of scattering which is neglected in the these theories.

Aygün et al. [17–19] have transmitted ultrasonic signals through water saturated stereolithograpical bone replicas in the form of 57 mm cubes with microstructural dimensions that are 13 times real scale at normal angle and oblique angles. Remarkably, it is found that the expected occurrence of scattering does not cause significant discrepancies between predictions and data at 100 kHz (which would be equivalent to 1.3 MHz in real bone), perhaps as a consequence of the fact that the samples behave as low pass filters.

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http://dx.doi.org/10.1016/j.apacoust.2014.07.011
0003-682X/

The aim of this paper is to investigate further ultrasonic wave transmission measurements on porous rigid ceramic (see Fig. 1) immersed in water at 1 MHz as a function of angle of propagation. Predictions of the anisotropic Biot–Allard model allowing for angle-dependent elasticity and angle-and-porosity dependent tortuosity have been compared with measurements made in a fluid (water) filled tank at 1 MHz.

2. Measurements

A procedure given by Fellah et al. [8] has been used to carry out measurements on porous rigid ceramic immersed in water filled tank with transducers (see Fig. 2). Two broadband Panametrics A 303S plane piezoelectric transducers having 1 cm diameter with 1 MHz central frequency have been used. 400 V pulses are provided by a 5058PR Panametrics pulser/receiver. Electronic interference is removed by 1000 acquisition averages.

Porous ceramic is obtained by mixing clay and plastic then burning the plastic in a kiln at Laboratory of Acoustics and Thermal Physics at K.U. Leuven. Porous ceramic used for measurements is in the form of 65 mm squares with 30 mm thickness. The measurements have been made parallel to trabeculae direction starting from 0° up to 45°. One incident (reference) signal generated by 1 MHz transducers and transmitted over corresponding path lengths in fluid (water) shown in Fig. 3a, and its spectra is shown in Fig. 3b, respectively. Reference signal was used as an initial signal when analyzing transmission data for porous ceramic.

Fig. 1. Picture of rigid porous ceramic.

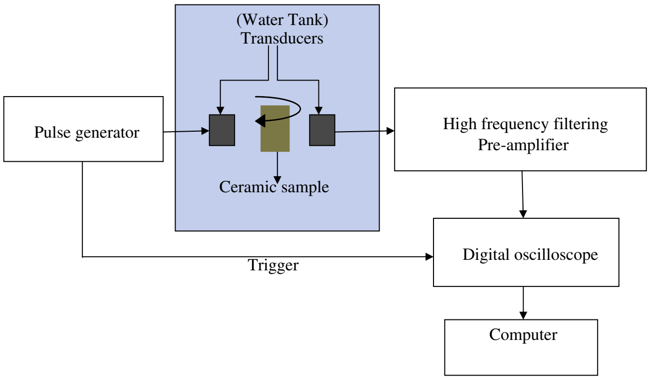

Fig. 2. Experimental setup for ultrasonic measurements.

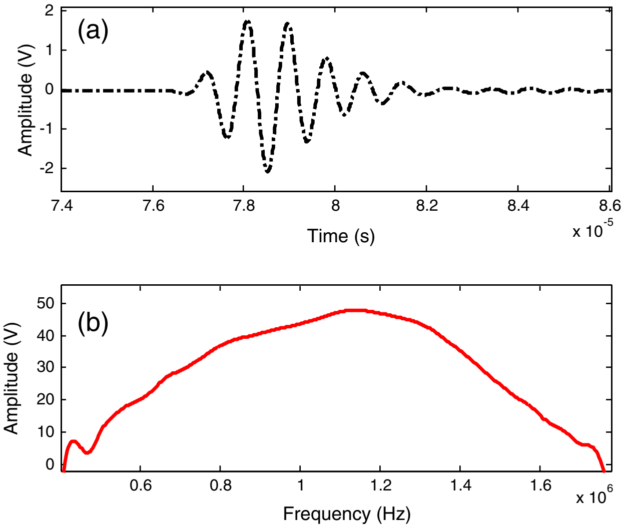

Fig. 3. (a) Inicident signal for porous rectangular ceramics versus time, (b) its spectrum versus frequency at 1 MHz.

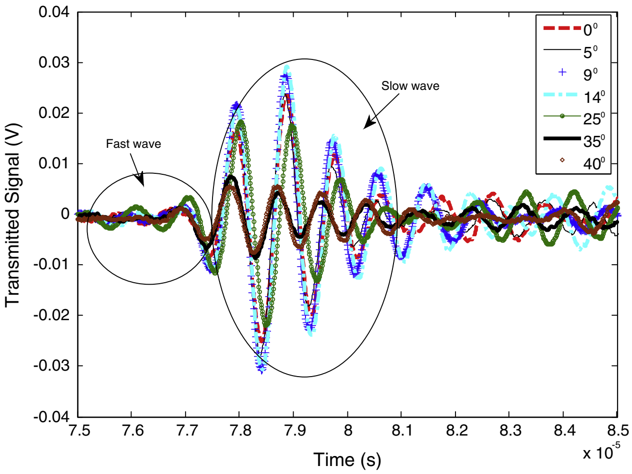

Fig. 4. Comparison of measured transmitted waveforms through porous ceramic versus time for different angles of propagation.

To vary the angle of incidence, ceramic was revolved around its central axis. For rotation angle, θ, measured from the normal, the transmission path becomes $L_{TP} = L \cdot \cos(\theta)$ where L is the sample thickness. The distance between two transducers was 115 mm and this distance was kept same throughout of measurements. Measured variations of transmitted signals through rigid porous ceramic as a function of angle of propagation are shown in Figs. 4 and 5, and the corresponding spectra for some of angle of propagation are shown in Fig. 6. The variation in the signals transmitted through the ceramic is mainly in amplitude rather than in the structure of the waveforms. There is a variation in the amplitude and the structure of the waveform at 30° (see Fig. 5). Varying angle of propagation from 0° to 45° shifts the peak amplitude of waveforms towards right-hand-side because the transmission path length has been increased from 30 mm to 42.43 mm. The initial parts of the measured transmitted waveforms are identified as the fast wave in which the fluid (water) and solid (ceramic) move in phase while the second and major parts of the transmitted waveforms can be identified as