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Simulation of ultrasonic wave propagation in anisotropic cancellous bone immersed in fluid

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ABSTRACT

Cancellous bone at the macroscopic level is known as being a two-phase anisotropic material composed of a solid rod-like or plate-like skeleton filled with viscous fluid. Quantifying the mechanical properties of cancellous bones by using ultrasound techniques should take into account these complexities. This paper proposes a model to investigate the transient ultrasonic wave propagation in a cancellous bone immersed in an acoustic fluid. A finite element time-domain model based on $\boldsymbol{u}^s - \boldsymbol{w}$ formulation is developed to consider an anisotropic porous medium (Biot's model) coupled with two acoustic fluids. Some numerical results are shown to illustrate the influence of the bone anisotropy to the reflection and transmission of plane waves in a human cancellous bone specimen.

1. Introduction

During the last decade, using of quantitative ultrasound (QUS) techniques for measuring mechanical properties of bone has received significant attention, particularly for its potential in estimating the bone fragility or fracture risk. The measurement is based on the estimation of the speed of sound and the attenuation of the wave transmitted through the bone. However, the interpretation of QUS measurements raises numerous problems because of the great complexity of the bone material which is a porous, anisotropic and heterogeneous medium. Two types of bone may be distinguished: cortical (compact) and cancellous (trabecular or spongy) bone. In cortical bone, porosity varies between 5% and 10%. Cancellous bone is much more porous with porosity ranging from 50% to 90%. Cancellous bone at the macroscopic level is known as to be a two-phase anisotropic material composed of a solid skeleton (an assembly of rod-like or plate-like trabeculae) filled with viscous fluid (the marrow).

The acoustic modeling of cancellous bone is relatively difficult in comparison with that of the cortical bone due to its greater complexity. For the *in vitro* studies of the ultrasonic wave propagation in cancellous bone, most ultrasound devices use the through-transmission measurement on the bone sample to determine broadband ultrasound attenuation (BUA) and speed of sound (SOS) [1–11]. Different theoretical models have been proposed: Biot's model [1,2,4–6,10,12], multilayer fluid–solid model [7] or μ-CT based model [11,13].

It has been shown that both mechanical properties and structural configuration of trabeculae strongly influence the wave characteristics. By examining experimentally the ultrasound wave propagation in bovine cancellous bone, two distinguished wave modes were observed propagating in the direction parallel to the main trabecular alignment [5]. The fast and slow

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modes correspond to the in-phase and out-of-phase relative motions between the fluid and solid, respectively. On the other hand, when considering the wave propagation in the direction perpendicular to the main trabecular alignment, only a single wave mode was observed. It has also been shown that numerical models based on Biot's model could predict the sound speed of the two waves in good agreement with experimental results [6]. By using Biot's equations, other authors [1,4,12] investigated the influence of the porosity, permeability or tortuosity on the propagation mechanism of *in vitro* ultrasonic waves. In these studies, the beam axis was assumed to be parallel to one of the principal directions of the bone specimen material (either parallel or perpendicular to the main trabecular alignment) and the transmitted waves were considered as plane waves. As a consequence, it was sufficient to use different sets of isotropic material properties to study the wave propagations in the principal directions of an orthotropic medium. Moreover, a simplified geometry and a linear elastic homogeneous material model were considered, which allowed to use a semi-analytical [4] or finite-difference [6] method to simulate the transient ultrasound wave transmission. To the best of our knowledge, the use of finite element method (FEM) has not yet been employed for this problem. However, FEM could be very advantageous in considering complex geometries as well as nonlinearities.

Some experimental studies have investigated the propagation of ultrasonic waves in an arbitrary direction through anisotropic cancellous bone [5,7]. The transmitted wave modes were shown to strongly depend on the angle between the wave direction and the main trabecular alignment. For numerical modeling of this problem, the Scheonberg's multilayer model has been used [7,14]. To the best of our knowledge, there are no published studies on the *in vitro* transmission test based on anisotropic Biot's model.

The objective of this paper is twofold. The first objective is to present an efficient numerical method for the simulation of ultrasonic wave transmitted in cancellous bone immersed in fluid. A finite element time-domain model of porous medium is proposed for simulating the high-frequency wave propagation in anisotropic cancellous bone. The second objective of this paper is to investigate the influence of bone anisotropy on the wave propagation. In particular, cancellous bone is modeled as an orthotropic medium and an ultrasonic wave pulse is emitted in a direction tilted with respect to one of the principal axes of the bone material. The interest of this study relies on the fact that, when a bone specimen is taken out from bone volume, the principal directions of the cancellous bone materials are not known precisely but are only estimated. Thus, when testing the specimen *in vitro*, the wave direction is likely to be misaligned with the principal directions of the material and this should be taken into account when analyzing experimental data.

The paper is organized as follows. After this introduction as background, in Section 2, the governing equations of a bone sample immersed in an ideal fluid are presented. The bone is modeled as an anisotropic saturated porous medium by using Biot's model in high frequency domain. Section 3 presents the weak formulation and the finite element implementation for the transient problem of a saturated porous medium coupled with a fluid. Section 4 begins with a numerical validation of the finite element solution. Then, the influence of the misalignment described above on the reflected and transmitted wave signals is investigated. Finally, conclusions and perspectives of this work are drawn in Section 5.

2. Statement of the problem

In this section we describe a simplified mechanical model of an *in vitro* transmission test performed on a specimen of trabecular bone. For this test, a slice-shaped bone specimen is immersed in a fluid. An acoustical source and a receiver are located in the fluid on opposite sides of the slice. The source emits a wave pulse which is recovered by the receiver. Travelling from the source to the receiver, the wave encounters the bone specimen, where it is in part reflected and in part transmitted. The characteristics of the reflected and transmitted waves depend on the bone material. Thus, their analysis may be usefully used to characterize the bone material and infer information on its structure.

2.1. Description of the geometrical configuration

A 2D schema of the test is represented in Fig. 1. We consider a bone layer embedded in two half-spaces occupied by fluid.

Let $\mathbf{R}(O;\mathbf{x}_1,\mathbf{x}_2)$ be the reference Cartesian frame where O is the origin and $(\mathbf{x}_1,\mathbf{x}_2)$ is an orthonormal basis for the space. The coordinates of a point $\boldsymbol{x}$ in $\mathbf{R}$ are specified by (x_1,x_2) and the time by t. The fluid occupies the two half-spaces Ω^f_1 and Ω^f_2. The bone layer occupies the unbounded domain Ω^b. The two plane interfaces between the bone (Ω^b) and the fluid domains (Ω^f_1 and Ω^f_2) are denoted by Γ^{bf}_1 and Γ^{bf}_2, respectively. The thickness of the bone sample is denoted by L. The acoustical source is located in the fluid domain Ω^f_1 and the receiver is located in the fluid domain Ω^f_2. We assume that the beam axis coincides with the axis $(O;\mathbf{x}_1)$. The dashed rectangle $ABCD$ represents a zone in which the wave field may be considered to be plane.

2.2. Governing equations

In what follows, we will denote by a superposed dot the time derivative, by ∇ and $\nabla\cdot$ the gradient and divergence operators in space, respectively. The symbol "$\cdot$" will denote the scalar product (between two vectors or tensors).