



**HAL**  
open science

# Numerical investigations of ultrasound wave propagating in long bones using a poroelastic model

Giuseppe Rosi, Vu-Hieu Nguyen, Salah Naili

► **To cite this version:**

Giuseppe Rosi, Vu-Hieu Nguyen, Salah Naili. Numerical investigations of ultrasound wave propagating in long bones using a poroelastic model. CFM 2015 - 22ème Congrès Français de Mécanique, Aug 2015, Lyon, France. hal-03444849

**HAL Id: hal-03444849**

**<https://hal.science/hal-03444849>**

Submitted on 23 Nov 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Numerical investigations of ultrasound wave propagating in long bones using a poroelastic model

G. ROSI , V.-H. NGUYEN , S. NAILI

Université Paris-Est, Laboratoire Modélisation et Simulation Multi Echelle, MSME UMR 8208 CNRS,  
61 av du Général de Gaulle, 94010 Créteil Cedex, France,  
giuseppe.rosi@univ-paris-est.fr

## Résumé :

*La réponse ultrasonore mesurée par la technique de transmission axiale (ATT) peut fournir des informations utiles concernant les propriétés matérielles et structurelles de l'os cortical. Pour la modélisation mathématique de propagation des ondes ultrasonores dans les os longs, la plupart des études suppose un comportement (visco-)élastique pour le tissu osseux cortical, en négligeant toutefois la pression interstitielle dans les pores. Ici, un modèle poroélastique anisotrope avec un gradient de propriétés matérielles est proposé pour décrire le comportement des os longs dans la gamme de fréquence ultrasonore. La simulation de propagation de l'onde dans le domaine temporel peut être effectuée de manière efficace en utilisant une méthode aux éléments finis semi-analytique. Le modèle proposé nous permet d'étudier l'influence de la présence de pores et leur répartition dans une couche d'os sur la vitesse des ondes acoustiques se propageant dans une couche d'os corticale couplée à la moelle et les tissus mous. Les effets de la fréquence de signal émis seront également pris en compte.*

## Abstract :

*Ultrasonic responses probed from axial transmission technique (ATT) may provide useful information about material and structural properties of cortical bone. For the mathematical modeling of ultrasonic wave propagation in long bones, most of studies assumed an (visco-)elastic behavior for cortical bone tissue by neglecting the interstitial pressure in the pores presented within this material. Here, a functionally-graded anisotropic poroelastic model is proposed for describing the behavior of long bones in the ultrasonic frequency range. The simulation of time-domain wave propagation can efficiently be carried out by using a semi-analytical finite element method. The proposed model allows us to investigate the influence of the presence of the pores and its distribution in a bone layer on the speed of sound propagated in a cortical bone layer coupled with the marrow and the soft tissue. The effects of emitted signal's frequency will also be examined.*

**Mots clefs :** Poroelasticity, Ultrasound, Axial Transmission, Bones

In an axial transmission (AT) device, the transmitter emits an ultrasound pulse (in a frequency range of 250 kHz - 2 MHz) that propagates along the bone's longitudinal axis to the receivers. Analysis of the probed signals may help to characterize reflections, conversion modes and interference of different kinds of waves (for instance, compressional, shear or guided waves) in the coupled system and, as a consequence, to assess the geometrical and physical properties of bones [1, 2]. However, current development of ultrasound AT techniques is still limited since the information potentially contained in the transmitted ultrasonic waves is not fully exploited. Moreover, inverse problem requires relevant mathematical models to be sufficiently precise for describing complex nature of bone tissues behaviors concerning absorption, anisotropy, porosity, etc.

In this work, we use a two-dimensional (2D) configuration for the description of the ultrasound wave propagation in long bones (see Figure 1). The 2D model has been shown to be appropriate in the

framework of simulation of the axial transmission technique [3]. This reduced model assumes that the effects of circumferential modes may be neglected. This assumption is no longer valid when the ratio between the cortical thickness and the bone radius is small. In that case, a 3D model would be more appropriated. An anisotropic poroelastic model is proposed to be used for describing dynamic behavior of

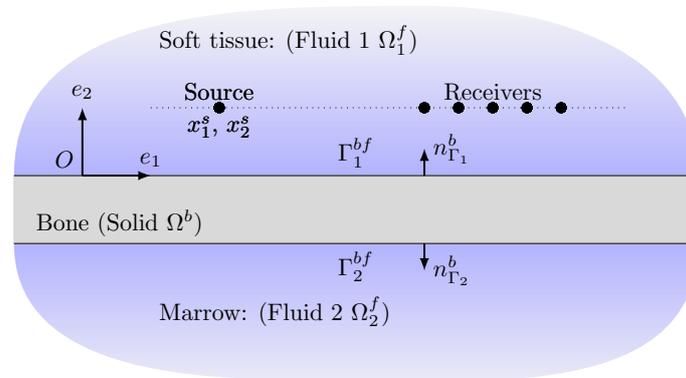


Figure 1: 2D geometrical description of the coupled system

cortical bone. The Biot theory, which has widely been used for modeling different kind of natural/artificial porous materials, will be employed here. Note that poroelastic models for bone were used in many works in the past for the analysis of the behavior of cortical bone tissue under low frequency loading or of ultrasonic wave propagation through cancellous bone. The use of a poroelastic model allows us to take into account the dynamics effects of fluid-filled pores as well as its heterogeneous spatial distribution in cortical bone. The objective is to focus on the investigation of the variation velocity of first arriving signal (FAS), which has been shown to be a relevant index for AT on bones.

From a computational point of view, the problem is solved as follows (for the details see [4]) : (i) the system of equations is firstly transformed into wavenumber-frequency domain by using a Fourier transform with respect to  $x_1$  combining to a Laplace transform with respect to  $t$ ; (ii) in the wavenumber-frequency domain, the equations in both fluid domains are analytically solved giving impedance boundary conditions for the solid layer that may be solved by the finite element method; (iii) the space-time solution is finally obtained by performing two inverse transforms.

In order to investigate the variations of porosity along the thickness of the bone, different case studies have been considered. A summary of all the considered configurations is in Figure 2.

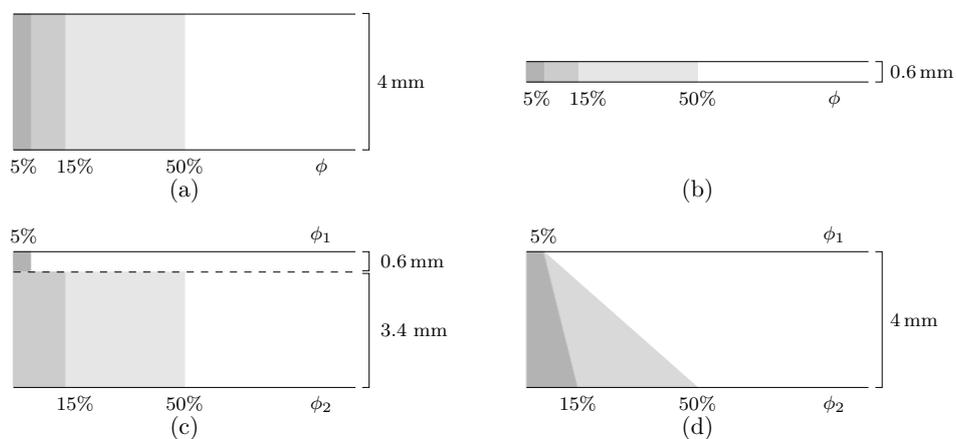


Figure 2: Configurations of interest for the numerical studies: (a) homogeneous bone with thickness  $h = 4$  mm ; (b) homogeneous bone with thickness  $h = 0.6$  mm ; (c) two-layer plate ; (d) gradient plate.

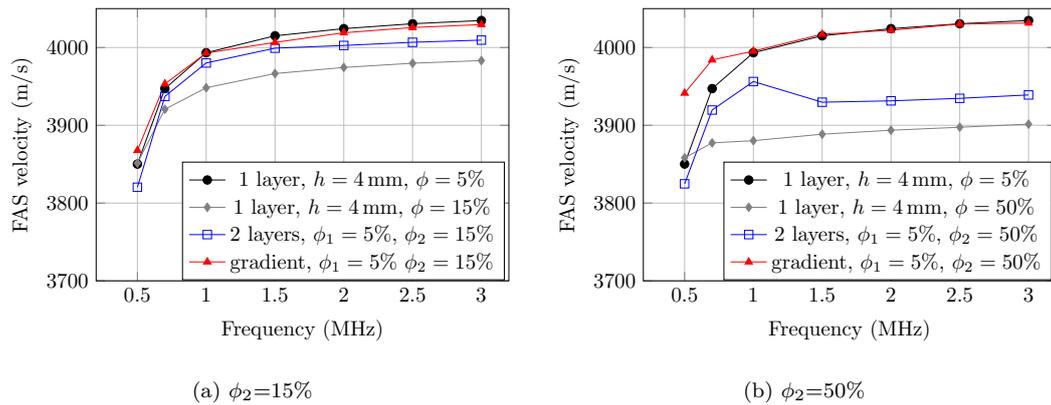


Figure 3: Velocity of the first arriving signal (FAS) in function of the frequency in the case of two-layer and gradient plates for  $\phi_2 = 15\%$  (a) and  $\phi_2 = 50\%$  (b), compared with the single layer of thickness  $h = 4$  mm.

Among the different numerical results obtained (see [5] for a complete presentation), one can study the comparison between the configurations that involve plates with overall thickness equal to 4 mm, precisely those corresponding to configurations (a), (c) and (d). In Figure 3(a) four curves are plotted and  $\phi_2$  is set to 15%. The curves corresponding to a gradient plate and an homogeneous plate with porosity  $\phi = 5\%$  are very close, while the two-layer plate places between that last curve and that corresponding to an homogeneous plate with porosity  $\phi = 15\%$ . This can be explained by the fact that the mean values of the porosity across the thickness are not the same for a gradient plate and a two-layer plate. However, we can conclude that the FAS velocity is more sensible to the variations of porosity near the surface.

Figure 3(b) refers to the same configurations, this time fixing  $\phi_2 = 50\%$ . As we can see, at low frequencies the only curves that is separated from the others is the one corresponding to a gradient plate, which on the contrary at higher frequency superposes to that of an homogeneous plate with porosity equal to 5%. For the other curves we can make the same considerations as for Figure 3(a), that will lead to the same conclusion that the plate is more sensitive to variations of the porosity near the surface. This results also show that the performing measures at different frequency is important to clearly discriminate between different configurations.

Further works will deal with comparing the poroelastic model's results with experimental measurement on some cortical bone specimens of which the detailed microstructural properties are known.

**Acknowledgement.** Giuseppe Rosi wish to thank the *Faculté de Sciences et Technologie* of the *Université Paris-Est Créteil* for the financial support.

## References

- [1] P. Moilanen, "Ultrasonic guided waves in bone," *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, vol. 55, pp. 1277–1286, June 2008.
- [2] P. H. F. Nicholson, P. Moilanen, T. Kärkkäinen, J. Timonen, and S. Cheng, "Guided ultrasonic waves in long bones: modelling, experiment and in vivo application," *Physiological Measurement*, vol. 23, pp. 755–768, Nov. 2002.
- [3] E. Bossy, M. Talmant, and P. Laugier, "Three-dimensional simulations of ultrasonic axial transmission velocity measurement on cortical bone models," *The Journal of the Acoustical Society of America*, vol. 115, pp. 2314–2324, May 2004.
- [4] V.-H. Nguyen and S. Naili, "Simulation of ultrasonic wave propagation in anisotropic poroelastic bone plate using hybrid spectral/finite element method," *International Journal for Numerical Methods in Biomedical Engineering*, vol. 28, pp. 861–876, Aug. 2012.

- [5] G. Rosi, V.-H. Nguyen, and S. Naili, “Numerical investigations of ultrasound wave propagating in long bones using a poroelastic model,” *Mathematics and Mechanics of Solids (Accepted for publication)*, 2015.