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Etude théorique et expérimentale de l'influence de la porosité sur les propriétés élastiques des os trabéculaire par la méthode ultrasonore

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LE MANS

This work relates to a theoretical and experimental study of the influence of porosity on the elastic properties through the propagation velocities of the longitudinal and transverse ultrasonic waves through the trabecular bone. The Schoch model is used to describe the vibro-elastic behavior of the cancellous bone. A quantitative analysis of propagation velocities depending on porosity is performed. Experimentally, a characterization of trabecular bone samples taken from the femoral head of cattle is achieved. For the determination of speed associated with each sample, an ultrasonic measurement technique in pulse mode by means of a pair of transducers nominal frequency of 500 kHz was used. The experimental results show a strong correlation between the bone density and the measured propagation velocities. We note a significant decrease of the longitudinal velocity in trabecular bone with increasing porosity. These results corroborate the theoretical results obtained using the Schoch model. This study confirms the sensitivity of the elastic properties with the variation of the bone porosity. This study also demonstrates the merits of using Schoch model for the description of the ultrasound propagation in cancellous bone.

1 Introduction

The techniques of quantitative ultrasound measurement are non-destructive. Their application to the exploration of bone tissue can tell us on the microstructure of the bone. Interest in the ultrasonic characterization methods continues to grow in recent years. They are inexpensive techniques, non-invasive and easy to implement. The ultrasound devices are used in clinical examinations in order to detect, identify and locate the pathologies in biological tissues. Diagnostic methods, ultrasonic, bone tissue is generally based on the estimation of speed and attenuation of ultrasonic waves that propagate in the bone tissue in order to determine the acoustic and geometric parameters of the bone by measures in vivo or in vitro [1].

Microscopic observation of bone tissue reveals two distinct structures. The first is made up of compact and dense bone said cortical bone. Its porosity is of the order of 5 to 10%. Flat and long bones are mainly made by this structure. The second, composed of cancellous or trabecular bone, occupies a larger volume than that of the cortical bone in the short bones. The trabecular bone forms a system of lamellas (trabeculae) which are arranged irregularly in space. This type of bone consists essentially of a matrix of connected rods and solid sheets (solid phase), immersed in a fluid medium (the bone marrow). It is highly porous (up to 90%). Acoustically, trabecular bone is much more complex material as the cortical bone. It is anisotropic, composite, porous and heterogeneous.

Knowledge of bone's elastic properties plays a fundamental role in the medical science [4]-[7]. The trabecular tissue failure could be used to study the effects of drug treatments, aging and disease in tissues : osteoporosis. The bone's mechanical properties are provided by measuring its elastic properties. Their quick and accurate measurements can help ensure the quality of its structure during the life cycle and to control its damage throughout the lifespan. The technique used in this study is based on the variations measurement of the ultrasonic properties, depending on the porosity. Then, the bone's elastic properties are deduced for each porosity rate. This requires the use of a theoretical model to study the propagation of ultrasonic waves and computational techniques and digital analysis (Schoch theory [8]). Finally, we represented the experimental method used and the experimental results for different bovine trabecular bones. They were taken from different bone sites : the femoral head and the femoral neck.

2 Modeling of the propagation of ultrasonic waves in porous bone

In this section we first recall the Schoch theory, the expression of the reflection coefficient at the interface between liquid and non-porous media semi-infinite which, under certain conditions, can be applied to porous media. Then, numerical simulation to analysis the Schoch theory reflectance.

2.1 Schoch theory

Figure (1) shows the reflection problem geometry of a plane longitudinal wave at the interface between a liquid and a solid.

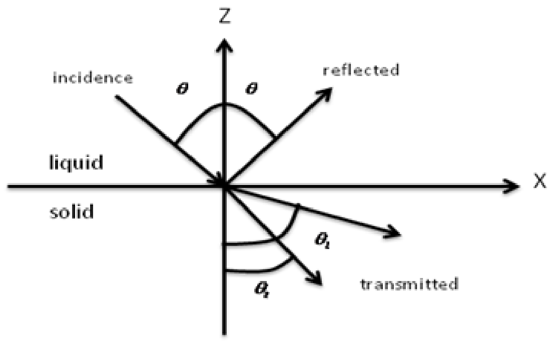

Figure 1 – Geometry problem

The angles of incidence, reflection and transmission to the law of Snell[7] :

$$k = k_{liq} sin(\theta) = k_l sin(\theta_l) = k_t sin(\theta_t)$$

Or k_{liq},k_l and k_t are respectively the wave numbers of the incident longitudinal waves, transmitted longitudinal and transverse.

2.1.1 Reflection coefficient

The reflection coefficient is defined as the ratio between the amplitude of the reflected wave and the incident wave. This coefficient is rewritten as a function of the incident angle by Schoch and that for a system of non-porous layers by the model Brekhovskikh. This coefficient is given by the following expression [7-10] :

$$R_s(\theta) = \frac{Z_l \cos^2 2\theta_t + Z_t \sin^2 2\theta_t - Z_{liq}}{Z_l \cos^2 2\theta_t + Z_t \sin^2 2\theta_t + Z_{liq}} \quad (1)$$

Or Z_{liq},Z_l et Z_t are respectively the acoustic impedances of liquid and solid.

2.1.2 Empirical relationships for acoustic parameters

The reflection coefficient is calculate by Schoch model at the interface between a coupling liquid and a homogeneous material and semi-infinite.

It is necessary to make some changes in the acoustic parameters in the case of porous materials, in order to introduce the porosity.
To solve this problem Phani and Maitra [11,12] proposed an expression for the longitudinal velocity of porous materials that take into account the morphology of the pore and is valid for all porosity values. This empirical relationship is written in the form :

$$V_l = V_{l0}(1-\phi)^p \tag{2}$$

Or V_l is the bone longitudinal wave velocity, ϕ is the bone porosity, V_{l0} is the bone longitudinal for $\phi = 0$, and p constant coefficient depends on the pore morphology.
For a medium saturated by a fluid, The equation of Phani is modified to take into account the speed of the fluid saturating, V_f. In this case, we have the relation :

$$V_l = V_{l0}(1-\phi)^m + \phi V_f \tag{3}$$

Since the fluid does not support shears, we chose an empirical relationship for the transverse velocity resembling that given by expression (3) :

$$V_t = V_{t0}(1-\phi)^s \tag{4}$$

Or V_t is the bone transversal wave velocity, V_{t0} is the bone transversal velocity for $\phi = 0$.
Phani has also studied the dependence of parameters m and s with the geometry of the pores.He noticed that the values of these quantities ranged between 0.5 and 1.5 for a relatively ordered porous structure. If the pores are cylindrical, m and s are close to one while for spherical pores values approaches 0.5.
Similarly to the average density of a particular porous body completely saturated, is related to the densities of non-porous solid ρ_s, saturating fluid ρ_f and the porosity ϕ by the following expression :

$$\rho_p = \rho_s(1-\phi) + \phi\rho_f \tag{5}$$

2.1.3 Numerical simulation

In the following figures(2-4), we will present numerical simulation results obtained from the Schoch theory when considering a homogeneous and non-porous medium corresponding to porous medium. Fig.2 show the variation of critical angle depending on the porosity of air-saturated bone(a)and water-saturated bone(b), fig.3 show the variation of velocities depending on the porosity of air-saturated bone(a)and water-saturated bone(b) and fig.4 show the variation of densities depending on the porosity of air-saturated bone(a)and water-saturated bone(b).

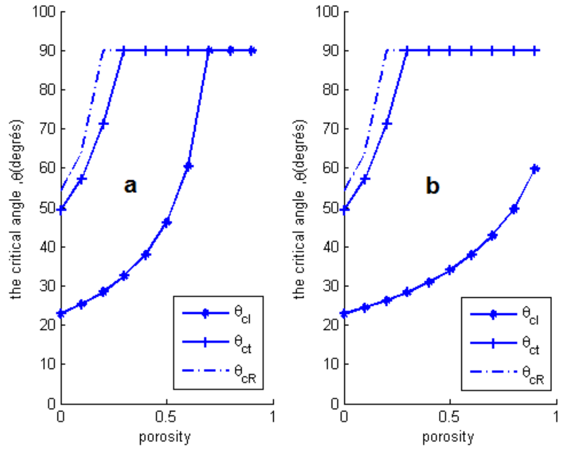

FIGURE 2 – Variation of critical angle depending on the porosity of bone saturated by air (a) and bone saturated by water(b)

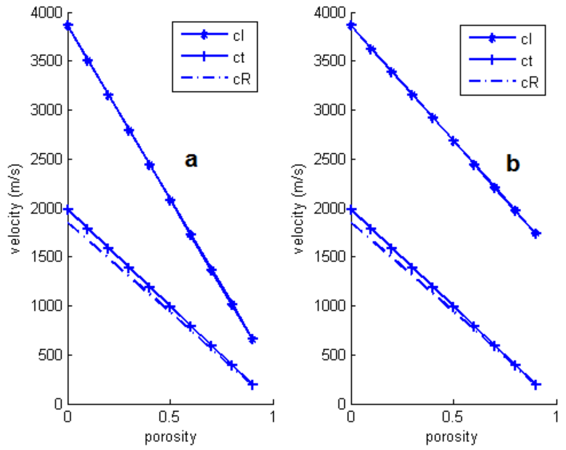

FIGURE 3 – Variation of velocities depending on the porosity of bone saturated by air (a) and bone saturated by water(b)

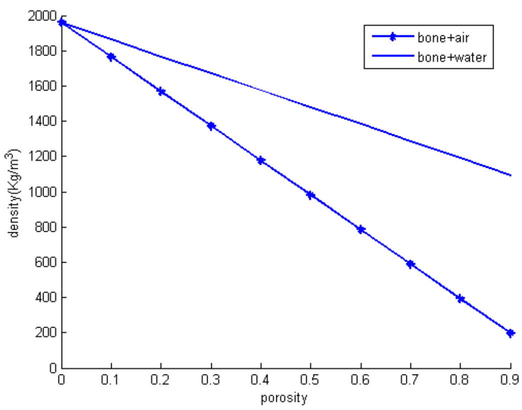

FIGURE 4 – Variation of densities depending on the porosity of bone saturated by air (a) and bone saturated by water(b)

3 Experimental results

3.1 Sample preparation

Bone tissue samples used in this experimental section are obtained from bovine bone. They were taken from different bone sites : femoral head and femoral neck[15-16]. To prepare the samples, a first rough cut was performed, to eliminate the cortical layer and uncover the trabecular bone alone. Then, a much finer cut was performed using a diamond saw to low speed rotating. Distilled water was used to lubricate and cool the saw in the second process to avoid damaging the surface of the specimen cut. During this process of sample preparation, a considerable portion of the bone marrow was removed. This uncontrolled loss of marrow samples, has modifies the wave propagation properties due to the presence of the air which replaces the lost marrow. To reduce this source of error, it was decided to extract all the marrow inside samples. These have all been washed using a pressurized water jet. They were then immersed in a solution of trichlorethylene for four hours and washed again in distilled water bath for 24 hours. This results in relatively clean samples.
The solid structure of the samples without the marrow obtained from the femoral head of a bovine bone shows the architecture of cancellous bone[18-19]. It provides information on pore size that differs from one point to another. This validates that the trabecular bone is a highly inhomogeneous medium.

FIGURE 5 – solid structure of the sample investigated

3.2 Experimental setup

Figure 6 shows the experimental setup of ultrasound measurements used during this work. The transducer and the samples are immersed in water. The transducer with the center frequency 5MHz. It transmits longitudinal ultrasonic waves to the bone through the water, after it receives the ultrasound waves through the sample. The transducer is excited by means of an ultrasonic pulse generator which also plays the role of an amplifier of the sensed signals. The generator is connected to a PicoScope to acquire the through signals. The signals picked up by the PicoScope are retrieved on a computer.
The signals displayed on the computer using a PicoScope National Instrument. PicoScope is controlled by the LabView software, so we have developed a platform in the friendly environment of the software to process ultrasound signals acquired in order to deduce the ultrasonic parameters of the trabecular bone.

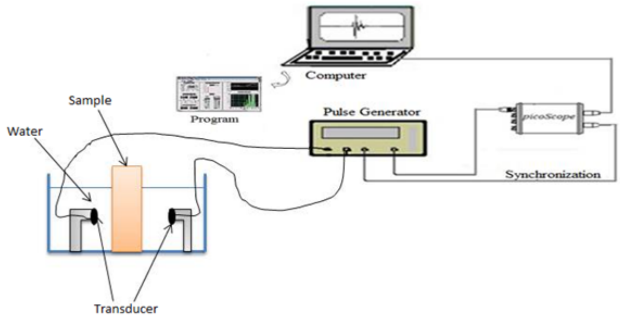

FIGURE 6 – Diagram of the experimental setup of the ultrasonic measurements in immersion in water.

3.3 The ultrasonic measurements

It is difficult or impossible to detect ultrasonic waves behind a whole bone as they are considerably attenuated by passing through the bone because of the high content of air and wide intercellular gaps in the structure bone. Thus, the reflection method was used for measuring the ultrasonic velocity within the bovine sample trabecular bone form of a parallelepiped plate. This non-destructive technique is very interesting to try the opportunity to assess the internal quality of the bone by making control of its inner layer only knowing that the bone quality control starts from the trabecular portion.

3.3.1 Measurement of ultrasonic velocity

For measuring the velocity of ultrasonic waves in the trabecular bone, we measure the flight time required for the wave to propagate the thickness thereof from which the ultrasonic signal backscattered by the bone. Thus the speed is calculated using the following formula :

$$V = \frac{d}{t_v} \tag{6}$$

d : Thickness of the bone plate.
t_v : Flight time
A number of measurements were made on samples of bone trabecular cattle. Samples of the parallelepiped-shaped femur head of variable thickness and density (therefore variable porosity) were cut. After the soft tissue and bone marrow were removed from bone samples, they were saturated with water. We measured the volume density, porosity, and the longitudinal speed of seven samples of bone trabecular bovine. This work is only an introduction to systematic study, already started to prepare a database of physical properties of trabecular bone skeletal bones from different sites. Therefore, most of our discussion will focus on what we have seen so far. Nevertheless, even with the results we have obtained, we can draw some interesting conclusions limited to samples studied

the longitudinal speed of the ultrasonic waves is an important parameter that provides information on certain properties of trabecular bone (tortuosity, porosity and density). It is related to the intrinsic properties of these bones. By observing the results shown in Table 3, we notice that the longitudinal speed varies from one sample to another. This variation is due mainly to the porosity. The analysis of our results shows that the sample has a low porosity, is the highest longitudinal velocity. As an example, the sample is cited 1. The latter has low porosity and high longitudinal velocity. This finding is in excellent agreement with the behavior of many other porous materials (Mavko et al, 2009).

This study confirms the sensitivity of the ultrasonic propagation velocity with variation in the porosity of the bone. It also proves the validity Schoch model for the description of the ultrasound propagation in cancellous bone.

We conclude that these results may provide a reliable method to obtain rapid characterization of bones, these results also are consistent with those found in the literature [2]. We found a good linear correlation between the porosity and the bulk density and between the porosity and the longitudinal velocity in the bone sample studied. This indicate the possibility of estimating the porosity of bones from the longitudinal velocity using a simple linear mathematical relationship. Comparison of our theoretical results with those obtained experimentally demonstrates a very good agreement, which constitutes a first step in validating our calculation program.

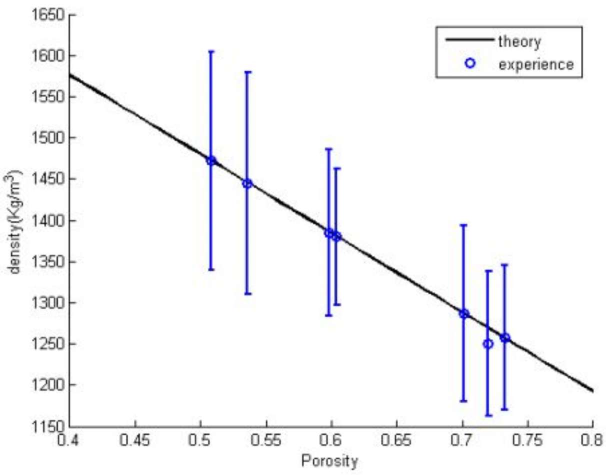

Figure 7 – Plot of the experimental values of the density as a function of the porosity. The line represents an empirical fit

4 Conclusion

This work aims to characterize the physical properties of the bone. First, Schoch theory was applied in this study to model the propagation of ultrasound in the trabecular bone. We had shown the reflection coefficient theoretically of an ultrasonic wave in a porous body provides information on the acoustic properties of the medium, the measures reflected waves through the plates of the bones several incidence angles to determine the longitudinal and transversal waves velocities of these bones. Second, we carry out an experimental study by an ultrasound method to determine the mechanical properties. Experimental measurements of the propagation rates obtained on bovine bones confirmed the predictions of the theory. Arguably, this model is well suited to describe a first approximation the ultrasonic wave propagation in porous bone. The velocity variation analysis for different modes depending on the porosity, showing the influence of this parameter on the ultrasonic wave's behavior. The determination of these velocities can lead to predict the bone healthy or bone pathological and can even discover its elastic parameters. The ultrasonic process is to be compared with other methods commonly used, much more restrictive. The ultrasonic method that used in this work allows easy, quick, inexpensive and non-destructive measurement for bone elastic properties. This method will remain among the reliable techniques to get a very interesting parameter in studies of the bone and knowing their bone density including porosity rate.

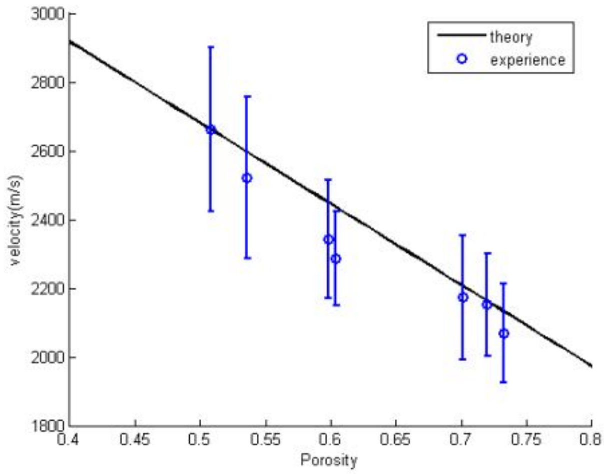

Figure 8 – Plot of the experimental values of the longitudinal velocity as a function of the porosity. The line represents empirical fit

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