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THE WIDE BAND ULTRASONIC SPECTROSCOPY IN STUDYING BONES AND POROUS IMPLANTS

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In the paper the method of wide band ultrasonic spectroscopy is applied to determination of the wave velocity and attenuation in a trabecular bovine bone and materials of bone implants. The theory of wave propagation in two-phase fluid saturated porous dissipative media, given by Biot (1956), is used in analysis of wave parameters in bone, instead of the usually applied theory of single-phase media. The analysis of attenuation coefficients and phase velocities of dilatational waves propagating in bovine bones and implants within the frequency range from 0.2 to 1.2 MHz has indicated remarkable influence of the internal structure of the materials on wave parameters. Potential directions of further exploatations of the results are considered.

Key words: saturated porous bones, implants, ultrasonic waves, phase velocity, attenuation

1. Introduction

Sustained growth of interest in theoretical and experimental studies of biological tissues has been recently observed. Among the phenomena, which draw the attention of researchers dealing with biomaterials are the problems of wave propagation.

The interest in wave propagation phenomena results mainly from the fact that measurements of ultrasonic waves are widely applied in medicine because of their noninvasiveness (e.g. ultrasonography) and effectiveness in diagnostic evaluation of tissues or organs.

When studying biological materials (e.g. liver, lungs, and bones) one should take into account that most of them, "working" in natural environment, are composed of solid porous matrix filled with interstitial fluid and thus have a multiphase nature. Therefore, these materials require a special treatment based on the mixture approach both in experimental studies and interpretation of the obtained results.

In general, there are two types of bone tissues classified depending on their micro and macroscopic features; the bone with low volume fraction of solid (less than 70%) is called a cancellous (trabecular or spongy) bone while that with above 70% it is classified as a cortical (compact) bone. In this paper, water saturated trabecular bovine bones have been studied. Moreover the water saturated as well as dry porous corundum, the materials used for a bone implant have been tested.

The two-phase approach to modeling of dynamical behavior of saturated bones and porous implants takes into account the interaction between fluid and solid phases due to their relative motion as wel as contribution of fluid in the stress transmission. The well known and widely applied mathematical model of dynamics of such materials was developed by Biot (1956). Biot's poroelasticity predicts two kinds of longitudinal waves, i.e. fast and slow ones, and a single shear wave. The existence of the all three wave modes has been confirmed experimentally by a number of researchers studying various saturated porous materials (cf Kaczmarek and Kubik, 1998).

In the present studies the fast compressional wave is analysed in a cancellous bone and porous corundum. The results of measurements of phase velocity and attenuation coefficient of the wave for water saturated trabecular bovine bone, and water saturated and dry porous implants are reported. The studies were performed using the wide band ultrasonic spectroscopy and immersion technique.

2. Theory

Since the specific features of dynamical behavior of cancellous bones and porous implants result from their two-phase nature, here the elementary properties of linear macroscopic model of wave propagation in saturated porous materials are introduced. The linear dynamic model of fluid-saturated porous solid was developed by Biot (1956), who used energetic method to derive two coupled balances of linear momentum including the information on the coupled stress-strain material response and interaction force between the phases. Hereinafter, the elements of such a model are reviewed and most important physical mechanisms causing attenuation and dispersion of ultrasonic waves are discussed. The model formulated in terms of the solid skeleton displacement $\boldsymbol{u}$ and fluid displacement $\boldsymbol{U}$, may be based on the following two linear momentum equations (cf Biot, 1956)

$$\begin{aligned}
\varrho^s(1-f_v)\frac{\partial^2\boldsymbol{u}}{\partial t^2} &= P\nabla(\nabla\cdot\boldsymbol{u}) + Q\nabla(\nabla\cdot\boldsymbol{U}) - N\nabla\times\nabla\boldsymbol{u} + \\
&\qquad +b\Big(\frac{\partial\boldsymbol{U}}{\partial t}-\frac{\partial\boldsymbol{u}}{\partial t}\Big) - \varrho_{12}\Big(\frac{\partial^2\boldsymbol{U}}{\partial t^2}-\frac{\partial^2\boldsymbol{u}}{\partial t^2}\Big) \\
\varrho^f f_v\frac{\partial^2\boldsymbol{U}}{\partial t^2} &= R\nabla(\nabla\cdot\boldsymbol{U}) + Q\nabla(\nabla\cdot\boldsymbol{u}) + \\
&\qquad -b\Big(\frac{\partial\boldsymbol{U}}{\partial t}-\frac{\partial\boldsymbol{u}}{\partial t}\Big) + \varrho_{12}\Big(\frac{\partial^2\boldsymbol{U}}{\partial t^2}-\frac{\partial^2\boldsymbol{u}}{\partial t^2}\Big)
\end{aligned} \tag{2.1}$$

where

$$b = \frac{f_v^2\mu}{K} \qquad\qquad \varrho_{12} = f_v\varrho^f(1-\alpha_T)$$

μ – viscosity of fluid
ϱ^f, ϱ^s – mass densities of fluid and solid material parameters, respectively
b, ϱ_{12} – coefficients expressing viscous and inertial forces between fluid and skeleton
f_v, – volume porosity
K – permeability
α_T – tortuosity.

The stress-strain relations for both porous solid and fluid phases used in (2.1) have the form

$$\begin{aligned}
\mathsf{T}^s &= \Big[(P-2N)\nabla\cdot\boldsymbol{u} + Q\nabla\cdot\boldsymbol{U}\Big]\mathsf{I} + N\Big[\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^{\top}\Big] \\
\mathsf{T}^f &= \Big[R\nabla\cdot\boldsymbol{U} + Q\nabla\cdot\boldsymbol{u}\Big]\mathsf{I}
\end{aligned} \tag{2.2}$$

In the above equations T^s and T^f represent the partial stress tensor in solid and fluid, respectively, and the parameters N, P, R, and Q are material coefficients which, in general, are complex value functions of frequency that refer to elastic or frictional properties of the solid skeleton and fluid.

The above introduced two-phase model predicts propagation of two different longitudinal waves (fast and slow) and propagation of a single shear wave.

The dispersion relation describing the two longitudinal waves has the form

$$\begin{aligned} &Yl^4 + \Big\{Hbjf - \Big[\varrho^s(1-f_v)R + \varrho^f f_v(2N+A) - H\varrho_{12}\Big]f^2\Big\}l^2 + \\ &+\Big[\varrho^f\varrho^s f_v(1-f_v) + \varrho_{12}\varrho\Big]f^4 - \varrho bjf^3 = 0 \end{aligned} \tag{2.3}$$

where

l – complex wave number

f – angular frequency and

$$\begin{aligned} &Y = (2N+A)R - Q^2 \qquad\qquad H = 2N + A + R + 2Q \\ &\varrho = (1-f_v)\varrho^s + f_v\varrho^f \end{aligned} \tag{2.4}$$

The dispersion relation for the shear wave reads

$$N[bjf - (f_v\varrho^f - \varrho_{12})f^2]k^2 + [\varrho^s(1-f_v)f_v - \varrho\varrho_{12}]f^4 - \varrho bjf^3 = 0 \tag{2.5}$$

where $j = \sqrt{-1}$, k denotes the complex wave number of the shear wave. The solutions to the above equations with respect to l and k give the information on frequency and structure dependence of the phase velocities v_i, and attenuation coefficients α_i of the two longitudinal waves

$$v_i = \mathrm{Re}\Big(\frac{f}{l_i}\Big) \qquad\qquad \alpha_i = \mathrm{Im}(l_i) \tag{2.6}$$

where index i refers to the fast or slow wave, and respective wave propagation parameters for shear wave

$$v_s = \mathrm{Re}\Big(\frac{f}{k}\Big) \qquad\qquad \alpha_s = \mathrm{Im}(k) \tag{2.7}$$

The fast wave results from the solid and fluid in-phase motion while the slow wave is associated with the out-of-phase motion of solid and fluid. The out-of-phase motion of constituents accompanied by the slow wave causes that the wave is strongly attenuated and usually, hardly observable in experimental studies of materials with low permeability.

In order to illustrate the existence and properties of the three waves in saturated porous materials in Fig.1 are shown the experimental results for

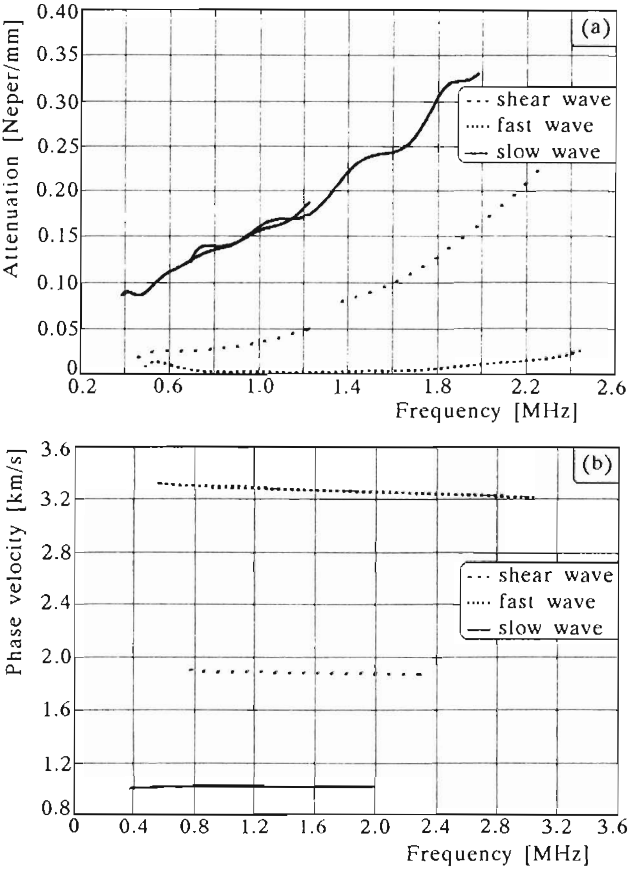

Fig. 1. Phase velocity and attenuation coefficient of fast, slow and shear waves, respectively, for water saturated porous glass (80μm)

attenuation and phase velocity of the waves in model material made of porous glass filled with water (details of the experimental procedure are given in Kaczmarek and Kubik (1998).

The average grain diameter in the model material is equal to 80μm. It is evident from the results that the attenuation of the slow wave is much stronger than that of the fast wave and the difference increases with frequency. The phase velocities of the waves differ significantly and slight dispersion (dependence of phase velocity on frequency) of the waves is visible.

Biot's two-phase model of porous materials takes into account the influence of structure parameters: porosity f_v, tortuosity α_T and permeability K, on propagation of the mechanical waves. The mechanisms causing attenuation and dispersion of the waves considered in the model are, in general, the macroscopic relative motion of fluid and skeleton and dissipation of energy in the materials of skeleton and fluid. The other sources of attenuation, not included in Biot's model are squirt flow, micro-shear waves due to fluid viscosity and scattering effects at microinhomogeneities which occur when the ratio of wavelength to average size of pores is not too high.

In Fig.2 the influence of scattering on attenuation of the fast wave is shown by comparison of the experimental results for model porous materials made of sintered glass particles of three different average grain diameters equal to 80, 140, and 275μm, respectively. The shift of the domains of strong dependence of attenuation on frequency for the studied materials indicates a significant role of scattering effects.

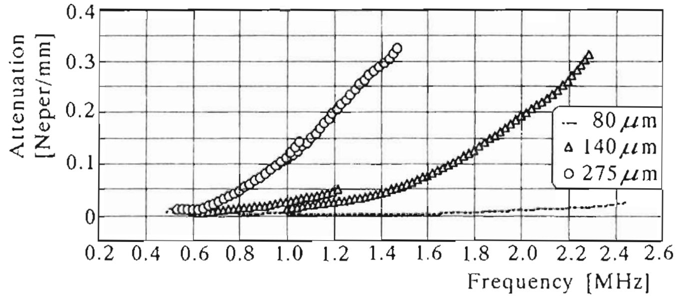

Fig. 2. Attenuation coefficient of the fast wave for water saturated porous glass of different average grain sizes (80, 140, 275μm)

Due to the above discussed phenomena one should expect that both the attenuation and dispersion of waves in the two-phase biomaterials, (cancellous bone and porous implant filled with water), are stronger and more frequency dependent than in most single-phase media.

3. Experiments

3.1. Specimens

A preparation of biological tissues may exerts a significant influence on the results obtained from ultrasonic examinations of materials. Thus, it is necessary to specify details of the applied preparation procedure.

Cancellous bone specimens about 40 mm in diameter and 7 and 14 mm in thickness, were cut from the distal epiphysis of two different fresh bovine femora. Then, the specimen preparation included removal of the bone marrow from pores by boiling the samples for about 1 hour and drying them.

The corundum porous materials, about 50 mm in size and 10 and 20 mm thickness, were provided by The Institute of Glass and Ceramics in Warsaw. More information about properties of the porous corundum implants is available from the reports (cf Bieniek and Oleszkiewicz, 1985; Święcki, 1993; Święcki et al., 1991; Rosiek et al., 1994).

Ultimately all examined specimens of trabecular bones and corundum have been saturated with water using vacuum technique.

3.2. Methods

The experimental investigations into ultrasonic waves in water saturated bones and porous implants are conducted using the pulse transmission method combined with the immersion technique, see Fig.3. The fast compressional wave was observed and its phase velocity and attenuation were determined.

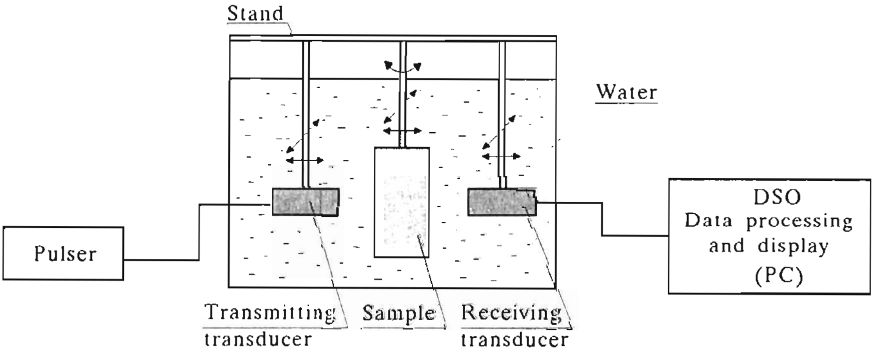

Fig. 3. Scheme of experimental setup for the applied immersion technique

The wave transducers are wide band with the central frequency of 0.5 and 1 MHz. The transmitting transducer is excited through a pulser by electric pulse of 350 V of $4\mu s$ duration. The receiving transducer is connected to the Link Instruments Digital Storage Oscilloscope (DSO) attached to a personal computer (PC). To sample the data the oscilloscope is triggered by a synchronisation signal generated by the pulser. The received signal sampled at a frequency up to 100 MHz and digitized is sent to the procedure of Fast Fourier Transform (FFT). The value of the sampling frequency is much higher then the Nyquist critical frequency and allows one to get high resolution of spectra in frequency domain. The FFT algorithm provides real and imaginary parts of the transformed signals in frequency domain which can be used to calculate the amplitude and phase spectra. In order to determine attenuation and phase velocity, the tests are performed on samples made of the same material but of different thicknesses (L_1, L_2), assuming that the energy of waves reflected at the boundaries in both cases is the same. In such a method the amplitude decay of the signal can be attributed solely to the increase in thickness of the samples. The idea of determination of ultrasonic parameters is shown in Fig.2. In the case the frequency dependent attenuation coefficient α, and the phase velocity v are defined as follows

$$\alpha(f) = \frac{1}{L_2 - L_1} \ln\left[\frac{A_1(f)}{A_2(f)}\right] \qquad v(f) = \frac{2\pi f(L_2 - L_1)}{2\pi n + \phi_2 - \phi_1} \tag{3.1}$$

where f is angular frequency, $A(f)$, $R(f)$ and $I(f)$ are amplitude, real and imaginary components of the Fourier transform of measured signals passing through the thinner (1) and thicker (2) samples, respectively.

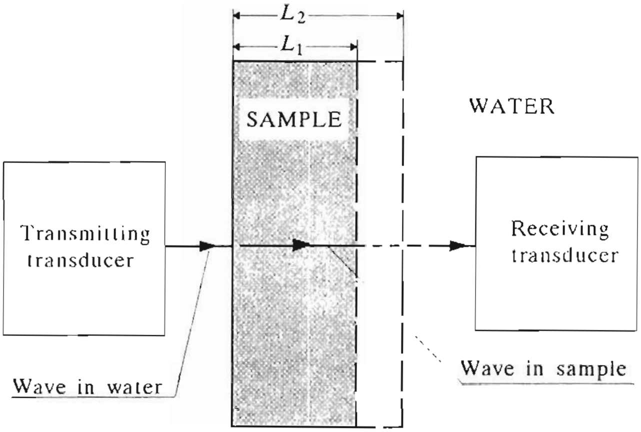

Fig. 4. Idea of ultrasonic parameters determination

An integer parameter n denotes the number of wavelengths, for given frequency, which are contained in the distance $L_2 - L_1$.

3.3. Results and discussion

In Section 2 the linear isotropic model of wave propagation in saturated porous materials was introduced with attention focused on the parameters describing the material structure and physical mechanisms that affect attenuation and dispersion of mechanical waves. In the following section the theoretical results are used to discuss the dynamical behavior of the materials examined by means of the ultrasonic method. The experimental results for phase velocity and attenuation coefficient of the fast compressional wave are reported.

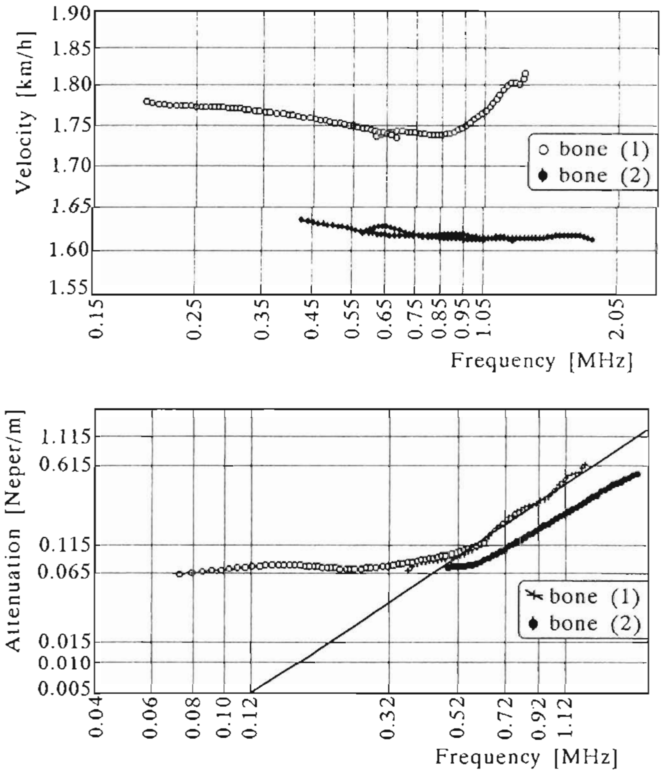

Fig. 5. Phase velocity and attenuation for two samples of trabecular bones saturated with water

In Fig.5 the ultrasonic parameters determined for two different trabecular bovine bones saturated with water are shown. The obtained results indicate that:

- In the frequency range from 0.2 to 0.5 MHz (for the first bone only), the attenuation coefficient is approximately constant (0.065 Neper/m), and the negative dispersion of phase velocity is observed,
- Above 0.5 MHz for first bone and above 0.6 MHz for the second one the attenuation is proportional to the second power of frequency, while the dispersion of phase velocity is different for the studied samples.

From the obtained data and studies presented in other papers (see e.g.

Kaczmarek et al., 1998) it can be concluded that the main attenuation mechanism at lower frequencies is the energy dissipation within the materials of phases (due to relative motion and/or deformation) while the effect of stochastic scattering appears for higher frequencies.

To formulate the relation between the wave propagation parameters and frequency for a fluid saturated porous material in the lower frequency range it is necessary to take into account the interaction due to the relative motion between phases represented within the two-phase model (see Section 2) through the interaction force

$$b\Big(\frac{\partial \boldsymbol{U}}{\partial t} - \frac{\partial \boldsymbol{u}}{\partial t}\Big) + \varrho_{12}\Big(\frac{\partial^2 \boldsymbol{U}}{\partial t^2} - \frac{\partial^2 \boldsymbol{u}}{\partial t^2}\Big)$$

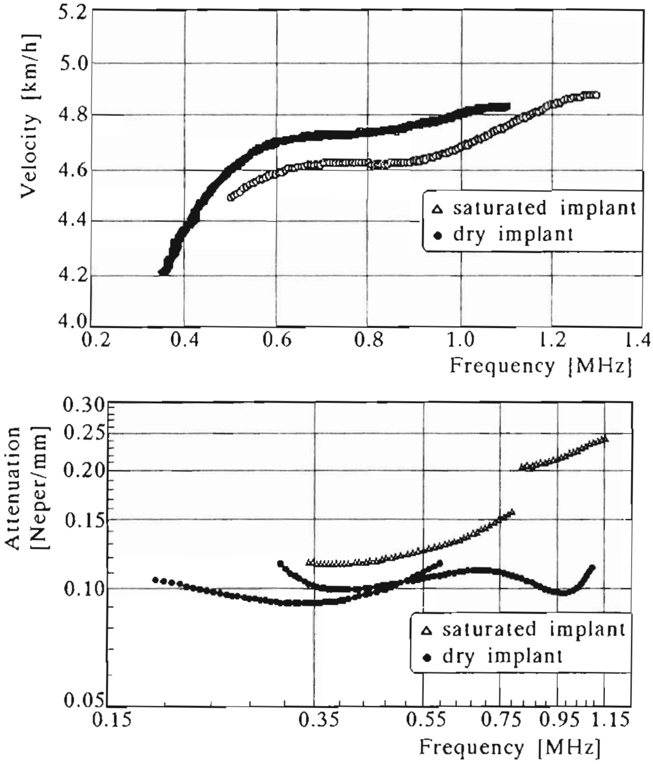

Fig. 6. Phase velocity and attenuation for dry and water saturated porous implants

The role of scattering is not included in Biot's model and requires further development (cf Kaczmarek et al., 1998). One should however notice that the lower bound of the frequency range where there is a visible influence of the scattering mechanism on attenuation depends on the ratio between the wavelength and characteristic size of pores, see Kaczmarek and Kubik (1998) and can be used to evaluate the latter parameter.

In Fig.6 the ultrasonic wave parameters for dry and water saturated implants are plotted as functions of frequency. It can be seen that the difference between velocities for dry and water saturated materials is not significant, while attenuation of waves, particularly in the higher frequency range is much lower for the dry sample than for the saturated one.

In Fig.7 the experimental results obtained for saturated cancellous bones and porous implants are compared. Considering the phase velocities in the given range of frequency a significant difference can be noticed. Taking into account the material densities (density of skeleton of corundum is approximately twice larger than the density of trabecular bone) it is evident that the rigidity of cancellous bone is much less than the rigidity of porous corundum.

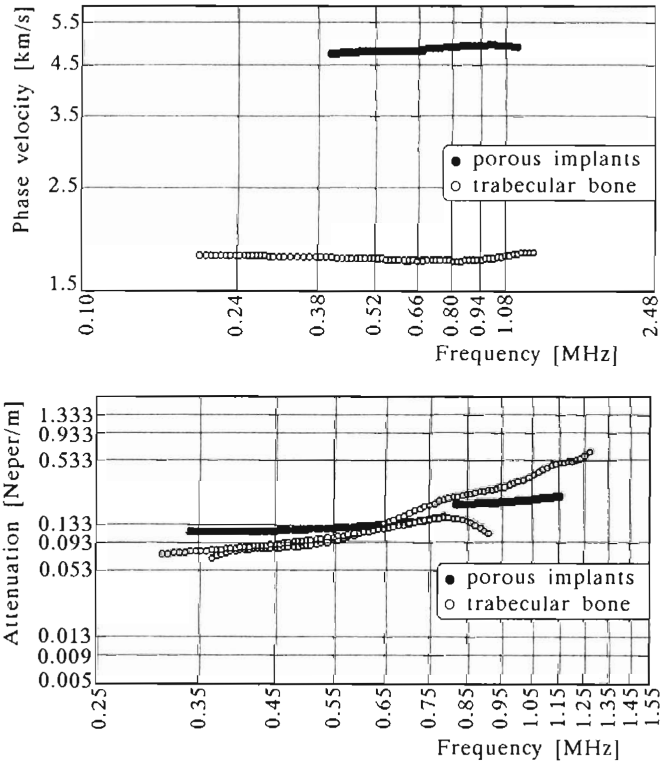

Fig. 7. Phase velocity and attenuation for the water saturated implant and trabecular bone

From the fact that the attenuation coefficients for both materials in the studied frequency range are comparable and microstructures of the materials are similar, it may turn out that the dominant mechanism of the attenuation is the energy dissipation due to relative motion of the phases.

4. Final remarks

The ultrasonic pulse transmission method and the spectral analysis of the measured signals appears to be an effective method for determination of wave parameters of bones and implants within a wide frequency range.

The results show that the attenuation and dispersion of ultrasonic waves in trabecular bones come from the two sources:

- Internal dissipation of energy
- Scattering effects.

The attenuation due to scattering exhibits properties of stochastic scattering. The comparison of the results for saturated bones and implants indicates that:

- Rigidity of implants is much higher than that for bones
- Attenuations are comparable.

The presence of the transition from non-scattering to scattering region of attenuation constitute a potential source of data on microstructure of the materials and should be studied to use the wide band ultrasonic technique for determination of characteristic pore diameters of biological and implant materials.

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Zastosowanie szerokopasmowej spektroskopii ultradźwiękowej w badaniach kości i porowatych implantów

Streszczenie

W pracy przedstawiono zastosowanie metody szerokopasmowej spektroskopii ultradźwiękowej do określenia prędkości i tłumienia fal w wołowej kości gąbczastej i ceramicznych materiałach biozastępczych.

Do analizy parametrów propagacji fal wykorzystano model Biota (1956) dwufazowego ośrodka porowatego nasyconego płynem z uwzględnieniem efektów dysypatywnych w odróżnieniu od zwykle stosowanych dla takich materiałów modeli ośrodków jednofazowych. Otrzymane wyniki dla współczynników tłumienia i prędkości fazowych fal podłużnych w badanych kościach i implantach, w zakresie częstotliwości od 0.2 do 1.2 MHz, wskazują na znaczacy wpływ struktury wewnętrznej materiałów na parametry propagacji fal. Rozważono możliwość wykorzystania otrzymanych wyników do oceny mikrostuktury porowatego materiału.

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