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In vitro measurements of ultrasonic parameters in saturated and dry bone tissues as a function of frequency

MICHAŁ PAKUŁA, MARIUSZ KACZMAREK, JÓZEF KUBIK

Chair of Environmental Mechanics, Bydgoszcz Pedagogical University,
ul. Chodkiewicza 30, 85-064 Bydgoszcz, Poland

The purpose of the paper is to describe the application of the method of ultrasonic spectroscopy to study wave propagation parameters: wave velocity and attenuation in saturated and dry trabecular bovine bones. The discussion concerns dilatational waves within the frequency range where visible influence of dissipation of mechanical energy, internal structure and scattering effects of the materials on wave parameters takes place.

Keywords: ultrasonics, trabecular bone, attenuation, phase velocity

1. Introduction

The growing interest in theoretical and experimental studies of biological tissues, and particularly in the problems of wave propagation in the materials, results mainly from the fact that measurements of ultrasonic waves have variety of applications in medicine because of their noninvasiveness (ultrasonography) and effectiveness in diagnosis. While considering the 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 multiphase nature and require special treatment both from theoretical point of view as well as in experimental studies and interpretation of the obtained results.

In the present paper the attention is focused on fast compressional waves in dry and water-saturated cancellous bones. The studies are performed using wide-band and ultrasonic spectroscopy along with the spectral analysis, and the results of measurements of phase velocity and the attenuation coefficient of the wave are reported.

The analysis of the results is based on a macroscopic model of wave propagation in saturated porous materials, [1, 4]. This two-phase model allows us to predict propagation of two different longitudinal waves, called fast and slow waves and propagation of a single shear wave. The fast wave is the result of the motion of solid and fluid in phase, while the slow wave is related to the motion of the solid and fluid out of phase. The slow wave is strongly attenuated and usually not observed in experiments.

The mechanisms causing attenuation and dispersion of the waves in biological tissues and considered in the model are, in general, the macroscopic relative motions of fluid and skeleton and dissipation of energy in materials of skeleton and fluid. The other sources of attenuation model are: squirt flow, micro-shear waves related to fluid viscosity and scattering effects at microinhomogeneities which occur when the ratio of wavelength to average size of pores is not too large.

2. Experiments

2.1. Specimens

A preparation of biological tissues for in vitro measurements may have significant influence on the results obtained from ultrasonic inspection of the materials. Thus, it is necessary to describe details of the preparation procedure of samples before measurements. Cancellous bone specimens, about 40 mm in length 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 bone marrow from pores by boiling it in water or in water solution of soda for about 1 hour and drying of the samples. Ultimately all tested specimens of trabecular bones have been saturated with water by vacuum technique.

2.2. Methods

The experimental investigations of ultrasonic waves in water-saturated bones are conducted using the pulse transmission method combined with the immersion technique (Fig. 1).

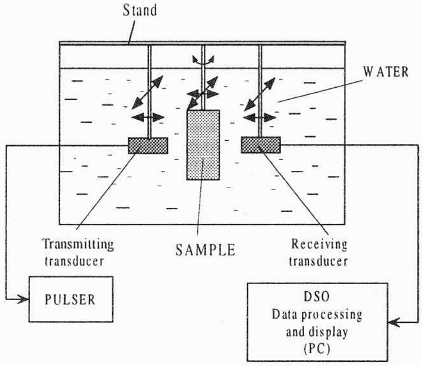

Fig. 1. Scheme of experimental setup and idea of determination of ultrasonic parameters for the applied immersion technique

The wave transducers are wide bands with the centre frequency of 0.5 and 1 MHz. The transmitting transducer is excited through a pulser by electric pulse up to 900 V of maximum 2 μs 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 synchronisation signal generated by the pulser. Received signal sampled at a frequency up to 100 MHz and digitized is sent to the Fast Fourier Transform (FFT).

In order to determine attenuation and phase velocity, the tests for samples of the same material but different thickness (L_1, L_2) are performed, assuming that energy of reflected wave 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 described elsewhere [3].

The frequency-dependent attenuation coefficient α and the phase velocity v in this case are defined as follows:

$$\alpha(f)=\frac{1}{L_2-L_1}\ln\frac{A_1(f)}{A_2(f)},$$

$$v(f)=\frac{2\pi(L_2-L)}{2\pi n+\phi_2-\phi_1},$$

where f is angular frequency, ϕ_1, ϕ_2 are phases and $A(f)$, $R(f)$ and $I(f)$ are amplitude, real and imaginary components of the Fourier transform of the measured signals passing through the thinner (1) and thicker (2) samples, respectively (Fig. 1). An integer parameter n denotes the number of wavelengths, for a given frequency, which are contained within the distance $L_2 - L_1$.

3. Results and discussion

In Fig. 2 the ultrasonic parameters determined for two different trabecular bovine bones saturated with water are shown.

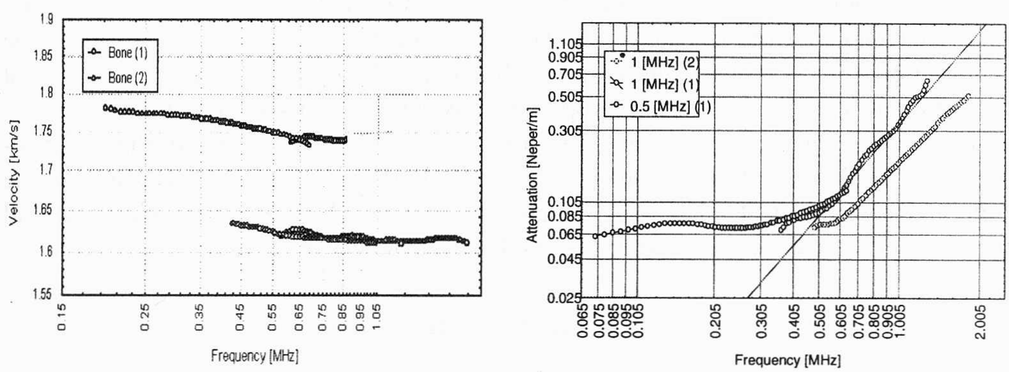

Fig. 2. Phase velocity and attenuation of trabecular bones saturated with water (boiled in water)

The obtained results prove that:

• in the frequency range from 0.2 to 0.5 MHz (the data for this frequency range are only for the first bone), the attenuation coefficient is approximately constant (0.065 Neper/m), and the negative dispersion of phase velocity is observed,

• above 0.5 MHz for the 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.

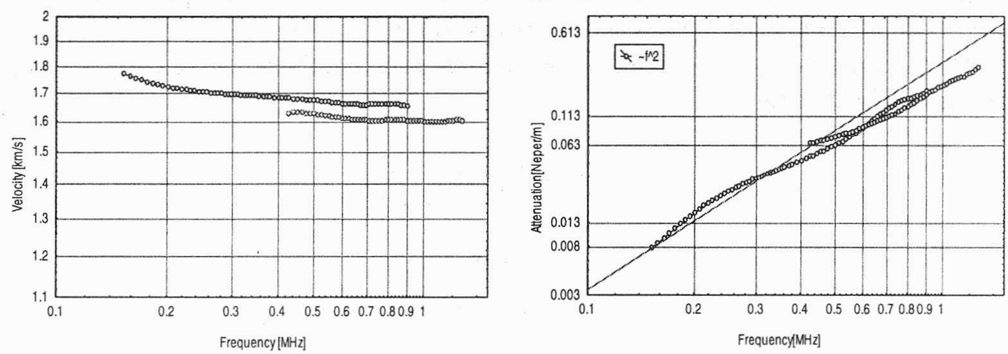

Fig. 3. Phase velocity and attenuation for samples prepared by boiling them in water solution of soda

Theoretical considerations (see [2], [3]) prove that the main attenuation mechanism in the lower frequency range is the dissipation of energy within the materials of phases (due to relative motion and/or deformation), while the effect of stochastic scattering appears at higher frequencies.

In Fig. 3 the attenuation coefficient and phase velocity obtained experimentally for water-saturated bovine bones prepared by boiling them in water solution of soda are shown.

The results prove that for material prepared in such a way, we do not observe the constant region of the attenuation coefficient, and the phase velocity exhibits negative dispersion. In the whole domain the attenuation is quadratic function of frequency. It is characteristic behaviour of materials in which the main source of attenuation of waves is the scattering effect (stochastic scattering). It is likely that the lack of the region of constant attenuation results from a change of properties of skeleton in soda-boiled bones.

The role of scattering is not included in the Biot model and requires further development, see [3]. One should notice, however, that the lower bound of the importance of the scattering mechanism of attenuation depends on the ratio between the wavelength and characteristic size of pores [2] and can be used to evaluate the latter parameter.

4. Final remarks

The ultrasonic pulse transmission method along with the spectral analysis of the measured signals appear to be the effective method for determining wave parameters of bones within a wide frequency range.

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

- internal dissipation of energy,
- scattering effects.

The attenuation due to scattering exhibits properties of stochastic scattering and the properties of the Rayleigh scattering in both water and lye-boiled bones are not observed.

The effect of attenuation from non-scattering to scattering region is a premise to use the wide-band ultrasonic technique for determination of characteristic pore diameters of biological materials.

References

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