FEASIBILITY OF BONE ASSESSMENT WITH LEAKY LAMB WAVES IN A BONE PHANTOM AND A BOVINE TIBIA

K. I. Lee and S. W. Yoon
Acoustics Research Laboratory and BK21 Physics Research Division,
Department of Physics, SungKyunKwan University, Suwon, Republic of Korea
swyoon@skku.ac.kr

Abstract

Quantitative ultrasound (QUS) technique is now widely used for non-invasive assessment of osteoporosis. The use of leaky Lamb waves is very attractive since they propagate throughout the cortical thickness of long bones. The feasibility of bone assessment with leaky Lamb waves is investigated in a bone phantom and a bovine tibia *in vitro* by using the axial transmission method. The bone phantom consists of Lucite plates with thicknesses of 1, 3, and 5 mm. The experimental results from the bone phantom show that the peak frequencies and the amplitudes of excited Lamb modes strongly depend on the frequency-thickness product. In the case of the bovine tibia, the A0 Lamb mode seems more sensitive to any change of elastic properties inside the bone plate due to damage or to cortical thickness change with aging and osteoporosis. This study suggests that the use of leaky Lamb waves is feasible for ultrasonic bone assessment.

Introduction

Ultrasonic guided waves are well-known to be suitable for characterizing thin plates and layered media [1,2]. A Lamb wave is a form of elastic perturbation that can propagate in a solid plate with free boundaries [3,4]. This type of wave was first described in theory by Lamb [5] in 1917, even, he never attempted to produce a Lamb wave. There are two groups of waves, symmetric and antisymmetric, that satisfy the wave equation and boundary conditions for this problem, and each wave can independently propagate.

The use of Lamb waves is very attractive since they propagate throughout the cortical thickness of long bones, which means that the entire thickness of the bone is interrogated. In the case of the immersion technique, a Lamb wave leaks out from a bone plate as it propagates; such a wave is called a leaky Lamb wave. The leaky Lamb wave technique uses specific modes of guided waves that are generated and detected through the mode-converted waves in the medium surrounding the plate.

In this study, an attempt is made to identify the leaky Lamb mode and the signal frequency that are most effective in bone assessment in the cortical layer. The main objective of the present study is to understand the effect of cortical thickness variation on the propagation of leaky Lamb waves since the cortical thickness changes with aging and osteoporosis, which has been shown to be a risk factor for fracture [6]. To this purpose, the propagation of leaky Lamb waves in a bone phantom and a bovine tibia *in vitro* is investigated for different leaky Lamb modes at various signal frequencies by using the axial transmission method, then the phase velocity dispersion curves as functions of the frequency-thickness product (MHz-mm) are determined for the cortical bone plate. The mechanical properties and the thickness of a plate can be determined from phase velocity dispersion curves.

Materials and methods

Bone phantom and bovine tibia

As a bone phantom of long bones, such as the radius, tibia, and femur, three Lucite plates with thicknesses of 1, 3, and 5 mm were used. The thickness values represent typical values of the cortical thicknesses of skeletal sites of the radius, tibia, and femur [7-9]. They were submerged in a water tank to simulate the surrounding soft tissue since the ultrasound velocity in water is close to that in soft tissue. The velocities of the longitudinal and the shear bulk waves propagating in this material were measured with a conventional ultrasonic technique. The longitudinal bulk wave velocity was measured as 2743 m/s, and the shear bulk wave velocity as 1427 m/s.

The tibia specimen used in this study was taken from one piece of bovine tibia. The proximal ends of the tibia were removed by using a rotary electric saw to make a hollow tube-shaped tibia without any soft tissue and marrow. The specimen was defatted by boiling for 1 hour in water. Cortical thickness of the tibia specimen was measured using calipers. The least irregularly shaped area of the tibia at which thickness was relatively well defined was chosen for ultrasonic measurements. The typical values of the longitudinal and the shear bulk wave velocities in the cortical part of the femur found in the literature are 4000 m/s and 1800 m/s along the axial direction, respectively [10]. They are used as input data to calculate the dispersion curves for the cortical bone plate.

Ultrasonic measurements

The schematic diagrams of the experimental setup for ultrasonic measurements with leaky Lamb waves are shown in Fig. 1. Ultrasonic measurements were performed in a water tank maintained at room temperature between 18 °C and 20 °C . In an attempt to make the tank less reverberant, anechoic lining plates were installed at the bottom of the tank. A spongy block with a thickness of 30 mm was used to exclude both the direct wave that travels in water directly from a transmitter to a receiver and the wave specularly reflected at the interface between water and the specimen. The spongy block is not shown in Fig. 1.

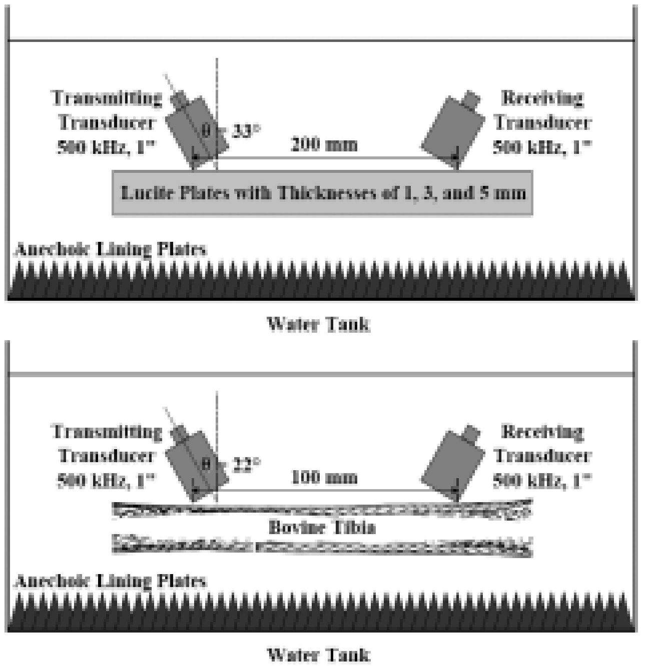

Figure 1 : Schematic diagrams of the experimental setup for ultrasonic measurements with leaky Lamb waves for the Lucite plate and the bovine tibia

Conventional wideband ultrasonic immersion transducers were used in all the experiments. A pair of transducers with a center frequency of 500 kHz (Panametrics V301, 1.0″ diameter) was placed as a transmitter and a receiver at the angle of θ (33° for the Lucite plate and 22° for the bovine tibia) to the interface as shown in Fig. 1, which is the longitudinal critical angle of incidence from water to the specimen. Individual Lamb waves are selectively excited by applying the coincidence principle. The angle of incidence, θ, was determined from Snell's law:

$$\theta = \sin^{-1}\left(\frac{c_w}{c_l}\right), \tag{1}$$

where c_w and c_l are the bulk wave velocities in water and the specimen, respectively. The transmitter was driven with a function generator (HP 3314A). The received signals, amplified by a preamplifier (SRS SR560), were analyzed with a 500 MHz digital storage oscilloscope (LeCroy LT322). The appropriate transmitter-receiver spacing was determined by taking into account the acceptable signal loss for the voltage sensitivity of the data acquisition system. Since the transmitter-receiver spacing in the current experiment is relatively short, five cycles of sine waves under the Hanning window were used to drive the transmitter without disturbing the received signals.

Results

Bone phantom: 1, 3, and 5 mm-thick Lucite plates

Figure 2 shows the response of a 350 kHz tone burst in a 5 mm-thick Lucite plate and gives a center frequency-thickness of 1.75 MHz-mm. The shape of the response wave packet indicates that very little dispersion is present over the frequency-thickness interval of the input signal. The wave packet shown in Fig. 2 was identified as the S1 mode from a measurement of its group velocity by using the time-of-flight method. The group velocity of the S1 mode was determined as 2615 m/s. As the frequency spectrum of Fig. 2 shows, the amplitude reaches a maximum at 342 kHz, which corresponds to the S1 mode, thus confirming that a pure S1 mode can be successfully launched in this frequency-thickness region.

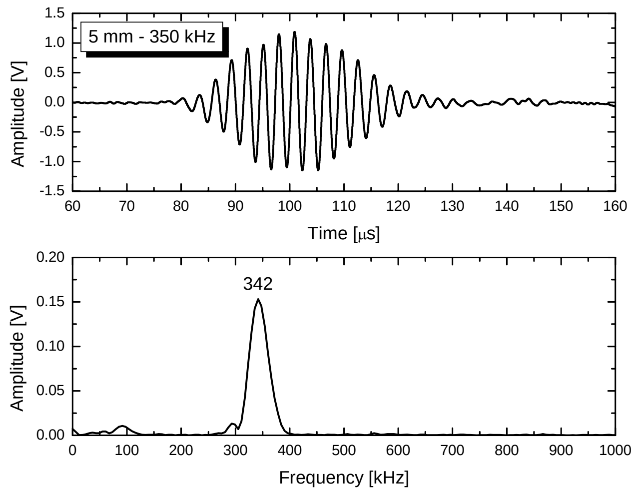

Figure 2 : Time-domain signal and frequency spectrum of the measured response for a 350 kHz tone burst in a 5 mm-thick Lucite plate

Figure 3 show the response of a 100 kHz tone burst in a 1 mm-thick Lucite plate and gives a center frequency-thickness of 0.1 MHz-mm. In this frequency-thickness region, i.e., lower than the frequency cut-off of the A1 mode, only the A0 and S0 modes can propagate along the Lucite plate. In the frequency spectrum, the amplitude reaches a maximum at 98 kHz, which corresponds to the S0 mode identified from a measurement of its group velocity. The group velocity of the S0 mode at 98 kHz was determined as 2466 m/s. Therefore, a pure S0 mode can be successfully launched in this frequency-thickness region.

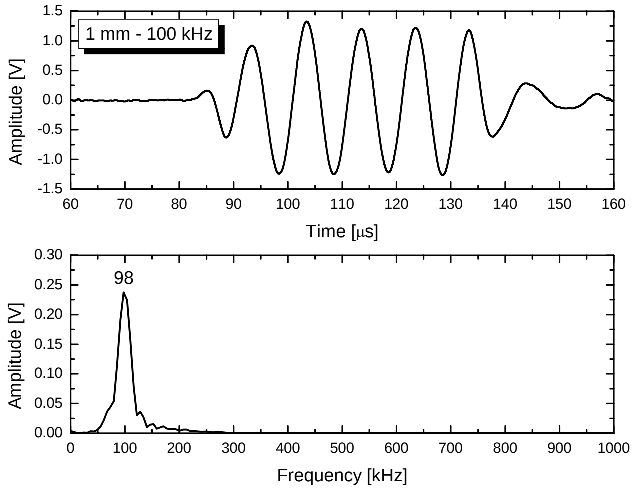

Figure 3 : Time-domain signal and frequency spectrum of the measured response for a 100 kHz tone burst in a 1 mm-thick Lucite plate

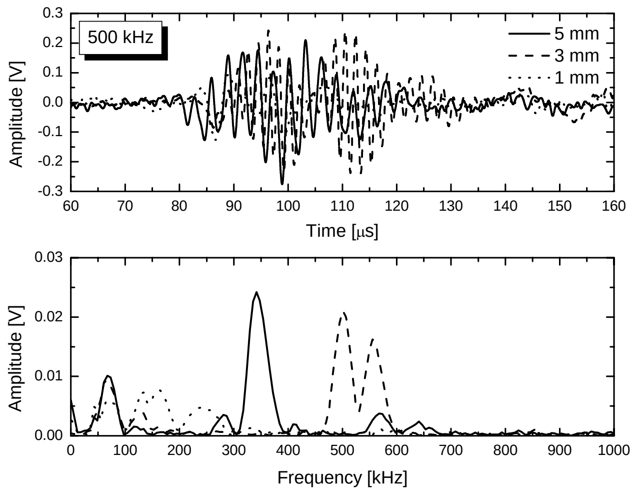

Figure 4 : Time-domain signal and frequency spectrum of the measured response for a 500 kHz tone burst in the 1, 3, and 5 mm-thick Lucite plates

Figure 4 shows the response of a 500 kHz tone burst in the 1, 3, and 5 mm-thick Lucite plates. These excitations give center frequency-thickness values of 0.5, 1.5, and 2.5 MHz-mm, respectively. The peak frequencies and the amplitudes of excited Lame modes are shown to strongly depend on the thickness of the plate. In the case of the 5 mm-thick Lucite plate, the maximum peak frequency at 342 kHz corresponds to the S1 mode. The response of the 3 mm-thick Lucite plate shows well-separated wave packets due to the presence of Lamb modes with different group velocities. The first arriving wave packet corresponds to the S1 mode at 555 kHz and the second one to the A1 mode at 500 kHz. In the 1 mm-thick Lucite plate, it is not possible to identify the excited modes from the response of the time-domain signal, though some evidence of modes is seen in the frequency spectrum below 300 kHz. It is noted that the peak frequency of the S1 mode is shifted from 342 to 555 kHz when the thickness of the plate is varied from 5 to 3 mm. It should be also noted that the excited Lamb modes are dominated by the S1 mode in the 5 mm-thick Lucite plate while they are more influenced by the A1 mode in the 3 mm-thick Lucite plate. These results show that the propagation of leaky Lamb waves is strongly affected by the thickness of the Lucite plate.

Bovine tibia: 2 mm-thick cortical bone plate

Figure 5 shows the response of a 200 kHz tone burst in a 2 mm-thick cortical bone plate. The excitation gives a center frequency-thickness of 0.4 MHz-mm. The response of the time-domain signal is similar to that of the 350 kHz tone burst in the 5 mm-thick plate. The shape of the response wave packet indicates that very little dispersion is present over the frequency-thickness interval of the input signal. The wave packet was identified as the S0 mode from a measurement of its group velocity by using the time-of-flight method. Its group velocity was determined as 3197 m/s. In the frequency spectrum of Fig. 5, the amplitude reaches a maximum at 204 kHz, which corresponds to the S0 mode, though some evidence of the A0 mode is seen at 250 kHz. Since the coincidence angle of 22° is appropriate for the S0 mode, the observed amplitude of the A0 mode is significantly less than its true value. Therefore, a pure S0 mode can be successfully launched in this frequency-thickness region.

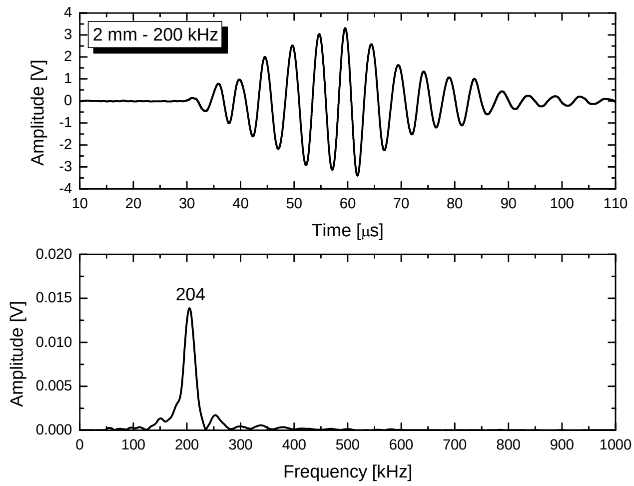

Figure 5 : Time-domain signal and frequency spectrum of the measured response for a 200 kHz tone burst in a 2 mm-thick cortical bone plate

Figure 6 shows the phase velocity dispersion curves as functions of the frequency-thickness product (MHz-mm) in a 2 mm-thick cortical bone plate. In order to determine the phase velocity of leaky Lamb wave in the bovine cortical bone plate, the receiving transducer was moved in the linear direction of wave propagation. The transmitter was excited by the one-cycle tone burst. The excitation frequencies were then varied from 100 to 500 kHz in 50 kHz steps, which give the center frequency-thickness values from 0.2 to

1.0 MHz-mm in the 2 mm-thick bone plate. The solid and dotted lines in Fig. 6 correspond to the theoretical phase velocities of the S0 and A0 modes calculated with the longitudinal bulk velocity of 4000 m/s and the shear bulk velocity of 1800 m/s. The squares (□) and circles (O) correspond to the experimental phase velocities obtained from the time-of-flight method.

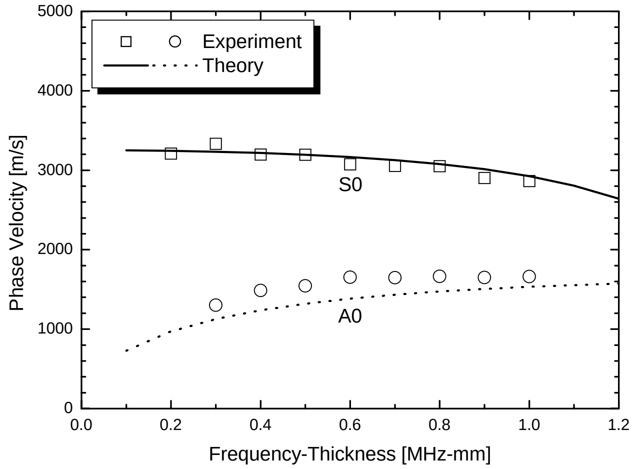

Figure 6 : Experimental and theoretical phase velocity dispersion curves as functions of the frequency-thickness product (MHz-mm) in a 2 mm-thick cortical bone plate

The S0 and A0 Lamb modes were consistently observed in the frequency-thickness region from 0.2 to 1.0 MHz-mm. In Fig. 6, however, the phase velocity of the A0 mode at 0.2 MHz-mm is not presented since it was not possible to identify the A0 mode in the response of the 100 kHz tone burst. The experimental phase velocities of the S0 mode are in good agreement with its theoretical curve. On the other hand, the experimental phase velocities of the A0 mode are somewhat higher than predicted values. The trends of both modes clearly correspond to predictions from the theory. It should be noted that both modes are affected by the frequency-thickness product but the effect is greater for the A0 mode from their normalized experimental phase velocities. Hence, in the frequency-thickness region from 0.2 to 1.0 MHz-mm where only the lowest Lamb modes can propagate, the A0 Lamb mode seems more sensitive to any change of elastic properties inside the bone plate due to damage or to cortical thickness change with aging and osteoporosis.

Conclusions

We have shown that both antisymmetric and symmetric leaky Lamb waves are successfully excited and detected in a bone phantom and a bovine tibia *in vitro* by using the axial transmission method. The experimental results show that the peak frequencies and the amplitudes of excited Lame modes strongly depend on the frequency-thickness product. It is also shown that the A0 Lamb mode seems more sensitive to any change of elastic properties inside the bone plate due to damage or to cortical thickness change with aging and osteoporosis. This study suggests that the use of leaky Lamb waves is feasible for ultrasonic bone assessment.

Acknowledgments

This work was supported by a Korea Research Foundation grant (KRF-2000-015-DP0178) and the BK21 Program of the Ministry of Education.

References

[1] L. Adler, M. de Billy, and G. Quentin, “Evaluation of friction-welded aluminum-steel bonds using dispersive guided modes of a layered substrate,” J. Appl. Phys., vol. 68, pp. 6072-6076, 1990.

[2] C.M. Hernandez, T.W. Murray, and S. Krishnaswamy, “Photo-acoustic characterization of mechanical properties of thin films,” Appl. Phys. Lett., vol. 80, pp. 691-693, 2002.

[3] I.A. Viktorov, Rayleigh and Lamb Waves, Physical Theory and Applications, Plenum Press, New York, 1967.

[4] A.H. Nayfeh, Wave Propagation in Layered Anisotropic Media with Applications to Composites, Elsevier, Amsterdam, 1995.

[5] H. Lamb, “On waves in an elastic plate,” Proceedings of the Royal Society of London. Series A, Containing papers of a mathematical and physical character, vol. 93, pp. 293-312, 1917.

[6] C.F. Njeh, D. Hans, T. Fuerst, C.C. Gluer, and H. K. Genant, Quantitative Ultrasound: Assessment of Osteoporosis and Bone Status, Martin Dunitz, London, 1999.

[7] C. Njeh, D. Hans, C. Wu, E. Kantorovich, M. Sister, T. Fuerst, and H.K. Genant, “An *in vitro* investigation of the dependence on sample thickness of the speed of sound along the specimen,” J. Med. Eng. Phys., vol. 21, pp. 651-659, 1999.

[8] H. Sievanen, S. Cheng, S. Ollikainen, and K. Uusi-Rasi, “Ultrasound velocity and cortical bone characteristics *in vivo*,” Osteoporosis Int., vol. 12, pp. 399-405, 2001.

[9] S. Prevrhal, T. Fuerst, B. Fan, C. Njeh, D. Hans, M. Uffmann, S. Srivastav, and H.K. Genant, “Quantitative ultrasound of the tibia depends on both cortical density and thickness,” Osteoporosis Int., vol. 12, pp. 28-34, 2001.

[10] S.S. Mehta and P.P. Antich, “Measurement of shear-wave velocity byultrasound critical-angle reflectometry (ucr),” Ultrasound Med. Biol., vol. 23, pp. 1123-1126, 1997.