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Excitation of ultrasonic Lamb waves using a phased array system with two array probes: Phantom and *in vitro* bone studies

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ABSTRACT

Long bones are good waveguides to support the propagation of ultrasonic guided waves. The low-order guided waves have been consistently observed in quantitative ultrasound bone studies. Selective excitation of these low-order guided modes requires oblique incidence of the ultrasound beam using a transducer-wedge system. It is generally assumed that an angle of incidence, θ_i, generates a specific phase velocity of interest, c_o, via Snell's law, $\theta_i = \sin^{-1}(v_w/c_o)$ where v_w is the velocity of the coupling medium. In this study, we investigated the excitation of guided waves within a 6.3-mm thick brass plate and a 6.5-mm thick bovine bone plate using an ultrasound phased array system with two 0.75-mm-pitch array probes. Arranging five elements as a group, the first group of a 16-element probe was used as a transmitter and a 64-element probe was a receiver array. The beam was steered for six angles (0°, 20°, 30°, 40°, 50°, and 60°) with a 1.6 MHz source signal. An adjoint Radon transform algorithm mapped the time-offset matrix into the frequency-phase velocity dispersion panels. The imaged Lamb plate modes were identified by the theoretical dispersion curves. The results show that the 0° excitation generated many modes with no modal discrimination and the oblique beam excited a spectrum of phase velocities spread asymmetrically about c_o. The width of the excitation region decreased as the steering angle increased, rendering modal selectivity at large angles. The phenomena were well predicted by the excitation function of the source influence theory. The low-order modes were better imaged at steering angle $\geqslant 30°$ for both plates. The study has also demonstrated the feasibility of using the two-probe phased array system for future *in vivo* study.

1. Introduction

Osteoporosis is a systemic skeletal disease characterized by gradual loss of bone density, micro-architectural deterioration of bone tissue, and thinning of the cortex, leading to bone fragility and an enhanced risk of fractures. Cortical thickness of long bone measurement has been investigated for the incidence of osteoporosis. Loss of cortical bone involves an increase of intracortical porosity due to trabecularization of cortical bone [1,2] and cortical thinning due to the expansion of marrow cavity on the endosteal surface [3]. The cortical thicknesses at distal radius and tibia in postmenopausal women with osteopenia were found to be thinner than those of normal women in an *in vivo* study using high-resolution peripheral quantitative computed tomography [4]. Recently, a high correlation was demonstrated between proximal humeral cortical bone thickness measured from anteroposterior shoulder radiographs and bone mineral density measured by Dual-energy X-ray absorptiometry in an *in vivo* study for osteoporosis diagnosis [5].

Ultrasound has been exploited to study long bones using the so-called axial transmission technique, where the transmitter and the receiver are deployed as a pitch–catch configuration with the receiver moving away from the transmitter. Since the acoustic impedance (density × velocity) of the cortex is much higher than those of the surrounding soft-tissue materials, the cortex is a strong ultrasound waveguide. The propagation of ultrasound is guided by the cortical boundaries and its propagation characteristics depend on the geometry (thickness) and material properties (elasticities and density) of the cortex and the surrounding tissues. Ultrasonic guided waves (GWs) propagate within long bone in their natural vibrational modes, known as guided modes at different phase velocities, which depend on frequency. The GWs travel longer distance and suffer less energy loss than the bulk waves because the boundaries keep most of the GW energies within the waveguide.

The application of GWs to study long bones is quite recent but the results so far are quite interesting. Nicholson et al. found the velocity of the fundamental Lamb mode A_0 differed by 15%

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between eight healthy and eight osteoporotic subjects (1615 m/s versus 1300 m/s) [6]. The same group studied a population of 106 pubertal girls and also found the velocity of a slow-traveling wave (1500–2300 m/s) consistent with that of the fundamental A_0 mode [7]. Protopappas et al. identified four low-order modes, S_0, S_1, S_2, and A_1 in an *ex vivo* study of an intact sheep tibia [8]. Lee et al. found a strong correlation between the phase velocities of A_0 and S_0 modes with cortical thicknesses in bovine tibiae [9]. Ta et al. found that the $L(0,2)$ mode was quite sensitive to the thickness change in the cortex [10]. Basically in most studies, the first few low-order guided modes have been consistently observed and further studied for their potential to characterize long bones.

Guided modes are dispersive and might come close together, posing a challenge for their identification. The ability to isolate the guided modes of interest is the key for a successful analysis of ultrasound data. Post-acquisition signal processing techniques such as singular value decomposition [11], $\tau - p$ transform [12], group velocity filtering [13], dispersion compensation [14], and the joint approximate diagonalization of eigen-matrices algorithm (JADE) [15] are viable methods to separate wavefields. Guided modes can also be selectively excited by using angle beam.

Preferential modal excitation and selectivity using angle beam is widely used in ultrasonic non-destructive testing and material characterization. It is generally assumed that given the compressional wave velocity of the angle wedge and an incident angle, only a phase velocity is generated via Snell's law. However in practice, the ultrasound beam has a finite beam size and does not generate just a single phase velocity for a given wedge angle. The element size of the transducer and the incident angle influence the excitation of the GWs within the structure, which is generally known as the source influence [16–18]. Instead of being excited with a definitive phase velocity (single excitation), GWs with a spectrum of phase velocities are generated at oblique incidence. For normal incidence, the phase velocity spectrum is very broad and dispersive, which implies infinite phase velocities to be excited, thus making mode isolation difficult. For a fixed size transducer, increasing the beam angle decreases the width of the phase velocity spectrum, thus generating fewer guided modes.

The use of angle beam to study long bone is very limited. Le et al. used a 51° angle beam to study bulk waves at receivers deployed downstream from the point of excitation [19]. Ta et al. used various angle beams to excite low-order longitudinal modes and was the first to mention briefly the concept of phase velocity spectrum in the bone community without much details [10,20]. Although a pair of transducers is still the most common means to acquire bone data, ultrasound array system has been used in axial transmission bone study [21]. The array system or multi-transmitter–multi-receiver system has many advantages over single-transmitter–single-receiver system. The former has better resolution because of the smaller element footprint, fast acquisition speed, accurate coordination of the receivers, and less motion-related problems. In case the system is a phased array (PA) system, beam steering is possible.

The objective of this work is to investigate the use of a PA system to excite guided waves in brass and bone plates. The system has two multi-element array probes with one acting as a transmitter and the other as a receiver. The acquired data are processed and transformed to the dispersion maps via an adjoint Radon transform. The theoretical dispersion curves based on plate models are used for modal identification. We attempt to explain the variation of guided-wave excitation with the incident angle using the source influence theory (SIT). The novelties of our work lie in our employment of two phased array probes and the use of Radon transform to estimate dispersion energy. To our knowledge, these have never been done in the bone community. While the SIT has been studied for a circular disk transducer, we find it interesting to apply the theory to our data acquired by a PA system.

2. Materials and methods

2.1. Preparation of samples

We performed experiments on a brass plate and a bovine bone plate. The brass plate was 6.3 mm thick with a 255 mm × 115 mm surface dimension. We prepared a bone plate from a fresh bovine tibia. The skin and soft tissue were removed. Using a table bandsaw, both ends of the tibia were cut and then the diaphysis was cut along the axial direction to make a plate. Both surfaces of the plate were sanded and smoothed by a disk sander. The resultant bone plate had a relatively flat (190 mm × 48 mm) surface area with a thickness of approximately 6.5 mm. The top face was polished further to prepare the surface ready for the placement of the probes.

2.2. Ultrasound phased array system

We used an Olympus TomoScan FOCUS LTTM Ultrasound PA system (Olympus NDT Inc., Canada) with two array probes as shown in Fig. 1a. The system has the following specifications: 0.5–20 MHz bandwidth, 20 kHz pulsing rate, 10-bit A/D converter, and up to 100 MHz sampling frequency. Real-time data compression and signal averaging are also available. The scanner has a high-speed data acquisition rate of 4 MB/s with maximum 1 GB file size and 8192 data point per A-scan (or time series). The unit is connected to a computer via Ethernet port. The Windows XP-based computer was loaded with the TomoviewTM software (Version 2.9 R6) to control the data acquisition process and to modify the parameters of the ultrasound beam such as scanning mode, beam angle, focal position, and active aperture. The acquired data can be exported to the computer for further post-acquisition analysis.

The scanner also supports multi-probe operations such as single-transducer-multi-element probe combination or two multi-

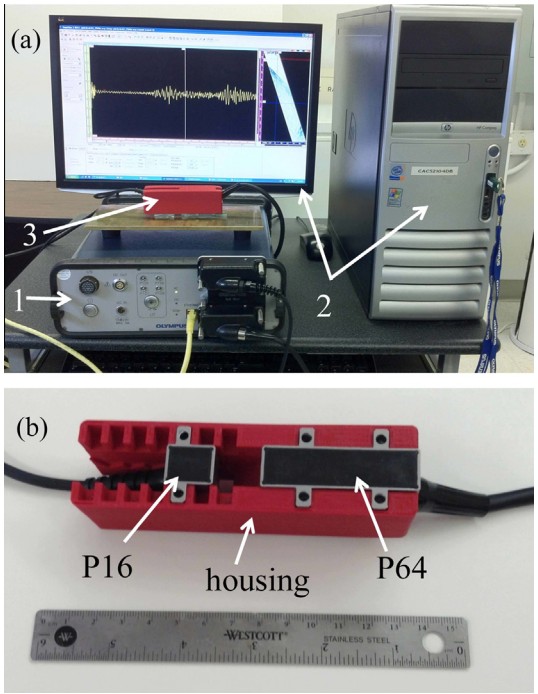

Fig. 1. The ultrasound phased array system: (a) The TomoScan FOCUS LTTM phased array acquisition system (1), the Windows XP-based computer with the TomoViewTM software to control the acquisition process (2), and the probe unit. (b) The housing with the 16-element and 64-element probes. The P16 was the transmitter array while the P64 was the receiver array.