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Ultrasonic bone parameter estimation using guided waves measured with multi-emitter and multi-receiver arrays

Josquin Foiret, Jean-Gabriel Minonzio, Maryline Talmant, Pascal Laugier

UPMC Univ. Paris 06, UMR 7623, LIP, 15 rue de l'école de médecine F-75005, Paris, France, josquin.foiret@upmc.fr

Our objective is to evaluate from ultrasonic measurements structural and elastic bone properties that are important determinant of bone strength. Different quantitative ultrasound techniques are currently developed for clinical assessment of human bone status. This paper is dedicated to axial transmission [1]-[4]: emitter(s) and receiver(s) are linearly arranged on the same side of the skeletal site, a long cortical bone, preferentially the forearm, a referenced site to predict fracture risk in case of osteoporosis as described in Figure 1a.

Figure 1a. Axial transmission ultrasonic device for clinical use.

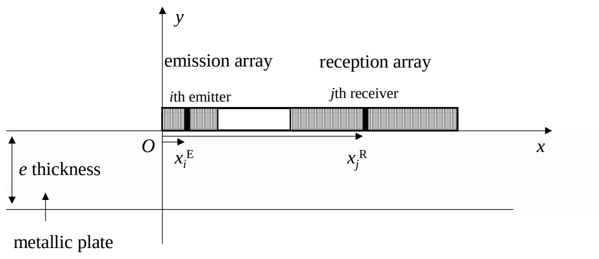

Figure 1b. Schematic geometry of a multi emitter and a multi receiver array used for the SVD based measurement of guided wave phase velocities..

Current clinical ultrasonic protocol consists in the measurement of the velocity of the earliest temporal event (FAS). In several clinical studies, the FAS velocity has been shown to discriminate osteoporotic patients from healthy subjects (see for example Ref. [4]). Moreover, in Ref. [5], bone elasticity was identified in a data base of actual in vivo measurements, using a stochastic model of bone anisotropy and a simplified geometry (plate). However FAS velocity measurement provide only one experimental parameter per patient and a set of ultrasonic parameter approach per patient might be necessary to evaluate both elastic and structural properties for each patient.

In this paper a multi parameter approach is proposed based on the guided waves phase velocities measurement. One of the simplest academic wave guide is the free isotropic elastic plate. In that case the wave numbers satisfy the Rayleigh-Lamb dispersion equation depending on three parameters: thickness, compression and shear velocities [7]. Experimentally, guided wave phase velocities can be obtained using the spatio-temporal Fourier transform of temporal responses measured at several distances. Clinical requirements and bone/soft tissue heterogeneities constrain the length probe to about 10 mm. Thus efficiency of conventional spatio-temporal Fourier transform is reduced [3], [6]. Signal processing to obtain reliable guided wave velocities is a key point. That is why a technique, taking benefit of using both multiple emitters and multiple receivers (see Figure 1b) has been proposed

[8]. The guided mode phase velocities are obtained using a projection in the singular vectors basis. Those are determined by the singular values decomposition (SVD) of the transmission matrix between the two arrays at fixed frequencies [8]. Applied on metallic plates SVD decomposition enabled us to measure accurately guided waves phase velocities according to the Rayleigh-Lamb dispersion equation for moderately large array (Figure 2a).

We have used the sensitivity of Lamb waves to elastic properties [9] to calibrate the probe by probing a copper metallic plate of known thickness. By minimizing the error between experimental and theoretical phase velocities, it has been shown that the two bulk velocities could be well determined (Figure 2b). The error function is defined using all the measurable modes as $\varepsilon = \frac{100}{N^{mode}} \sum_{n=1}^{N^{mode}} \frac{\left\| k_n^{bidir} - k_n^{theo} \right\|}{\left\| k_n^{bidir} \right\|}$, with k_n^{bidir} and k_n^{theo} the experimental and theoretical wave numbers. Alternatively, the specific sensitivity of each mode to the plate properties can be exploited separately.

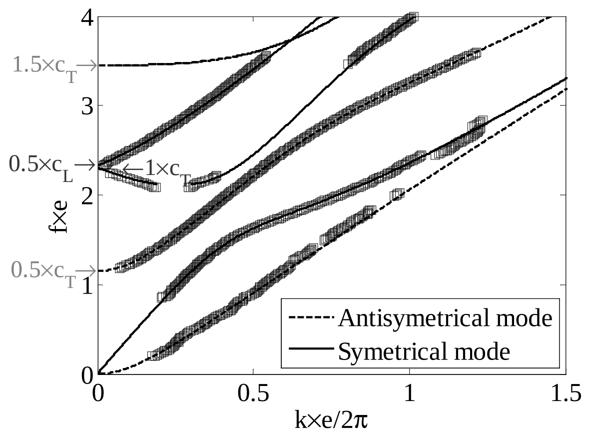

Figure 2a: experimental (black square) and theoretical (solid and dashed lines) dispersion curves for a 2 mm copper plate. The x-axis is the thickness/wavelength ratio and the y-axis the frequency*thickness product (MHz.mm). Theoretical Lamb curves are plotted for $c_L = 4675$ m.s^{-1} and $c_T = 2300$ m.s^{-1} ($\nu = 0.3403$).

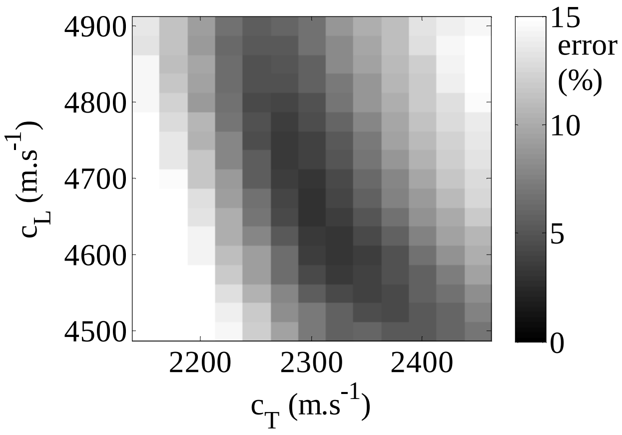

Figure 2b: error function ε for different compression and shear velocities (respectively c_L and c_T) for a 2 mm copper plate. The minimum was found for the couple of velocities (4675, 2300).

In vitro measurements on human radius are currently performed. Analysis is based on the whole set of measured bone modes and also on particular branches. Next step will be to define the closest reference wave guide model taking into account the geometrical and elastic bone properties. In particular, anisotropy and heterogeneity of bone makes that real problem challenging.

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