2E2-1

Numerical Study of Beam-Steering Ultrasonic Guided Waves in a Bone-Mimicking Plate

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1. Introduction

Ultrasonic guided waves (UGWs) present a promising tool for bone assessment. In comparison with the bulk waves, UGWs experience less attenuation, travel longer distance, and interact with larger portion of the bone. Axial transmission (AT) technique is commonly used to acquire data along the long bone. The technique employs emitter(s) and receiver(s) placed collinearly along the bone axis and on the same side of the bone sample [1]. The ultrasound signals, which propagate from the emitters and through the bone structures, are recorded by a receiver placed at different positions or a receiver array.

Exciting the UGWs traveling with particular phase velocities in bone structure is a subject of interest. According to the Source Influence Theory (SIT) [2], one can excite the UGWs in a narrow spectrum of phase velocities using incident angle of the ultrasonic beam. Phased array (PA) ultrasound system is a means to create a focused angle beam by time-delaying the excitation of the elements so that the overall wave front steers along a certain direction. Using ultrasonic phased array technique to study UGWs in bones is relatively new and the number of study is still limited.

In this work, the semi-analytical finite element (SAFE) method [4] is employed to simulate the UGW excitation in a bone plate model by beam steering, analogous to the UGWs measurements by Nguyen et al. [3]. The effect of the steering angle on the phase velocity spectra of the simulated signals will be discussed.

2. Material and Method

The bone plate is mimicked as a two-dimensional homogeneous, isotropic, and viscoelastic solid layer of a constant thickness ($h = 6.5$ mm). The mechanical properties are similar to those of bovine cortex (Tab.1) [3]:

Mass density ρ	1850 kg/m^3
P-wave speed v_P	4000 m/s
S-wave speed v_S	1800 m/s
P-wave attenuation α_P	5 dB/cm
S-wave attenuation α_S	11 dB/cm

Table 1: *Mechanical parameters of the bone model.*

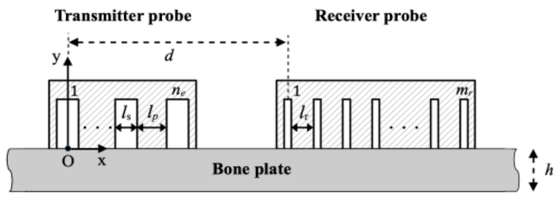

Fig. 1: *Configuration of the simulation.*

A phased array system is put in contact with the bone phantom (Fig.1). The transmitter probe has 5 elements with width 0.7 mm and pitch 0.75 mm. The n'th element generates a pulse pressure $s_n(t)$ with a specific time-delay, $t_n = n\tau$:

$$s_n(t) = A\sin[2\pi f_c(t-t_n)]e^{-4[f_c(t-t_n)-1]^2},$$

so that $s_n(t) = s_{n-1}(t-\tau)$. Here, f_c is the centre frequency, chosen to be 1 MHz. The incident angle is controlled through the time delay τ by $\sin\theta = \tau v_{ref}/l_p$ [5] with $v_{ref} = 1500$ m/s. The equations of motion which govern the propagation of wave fields are

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$$\begin{cases} \rho \ddot{u}_i - \sigma_{ij,j} = 0, \\ \sigma_{ij} = \left(\lambda \varepsilon_{kk} + \eta_\lambda \dot{\varepsilon}_{kk}\right)\delta_{ij} + 2(\mu \varepsilon_{ij} + \eta_\mu \dot{\varepsilon}_{ij}) \end{cases}$$

where λ, μ are the elastic constants and η_λ, η_μ are the viscosity coefficients, which can be calculated through the parameters given in Table 1.

The simulated wave fields are computed by the SAFE method [4] for 64 receiver's positions, evenly spaced from 22 to 67 mm relative to the first emitter. The dispersive phase velocities are derived by applying the Radon transform [6] on the time series.

3. Results and Discussion

The Radon panels are shown in Fig. 2 for different values of the steering angle.

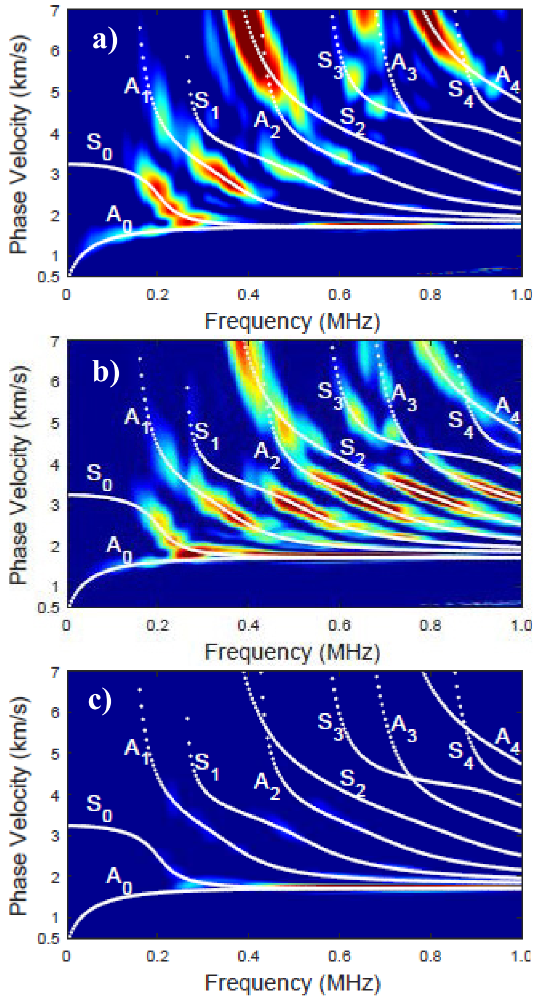

Fig. 2: *Radon panels of UGWs in the bone plate excited at different steering angles: (a) 0°, (b) 30°, and (c) 60°.*

For normal incidence (Fig. 2a), the clusters lie on the first five asymmetric (A_0-A_4) and five symmetric (S_0-S_4) modes, distributed in a wide range of velocity values, but more toward on the high-speed than on the low-speed regimes. Three high-velocity energetic GW spectra can be identified: two clusters above 5 km/s at the intersection of S_2 and A_2, and the intersection of S_4 and A_4; the A_3 mode with $v > 6.5$ km/s. In the low-speed regime for $v < 4$ km/s, the strong clusters are S_0, and A_1 for $f < 0.4$ MHz, and S_0 / A_0 between 0.55 and 0.8 MHz.

As the steering angle increases to 30° (Fig. 2b) the slow GWs are enhanced. Majority of the energy lie below 4 km/s. Seven low-speed GW clusters can be observed with high intensity including four first asymmetric modes A_0-A_3 and three first symmetric modes S_0-S_2. High-speed wave components still remain; however, they seem to give up some energy for the creation of slow GWs. For example, the strong GW cluster at the intersection between A_2 and S_2 in the case of normal incidence seems to transfer the energy to form two separate strong spectra, A_2 and S_2 below 4 km/s. Similarly, the fast A_3 transfers its energy to form a slow A_3 for $f > 0.8$ MHz. Continually increasing the steering angle will reduce gradually the fast GWs. At $\theta = 60^0$ (Fig. 2c) only A_0 and S_0 exist for $f > 0.45$ MHz. The result is in agreement with the SIT, which predicts the range of phase velocity becoming narrower as the steering angle increases.

4. Conclusion

By the SAFE method, the steering of ultrasound beam through a bovine cortex was simulated by adjusting the time of excitation of the emitter's elements while the propagation of the wave fields was computed by the SAFE method. The Radon panels display the spectra in agreement with the SIT prediction. Modal selectivity becomes more stringent as the steering angle increases.

Acknowledgements

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