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# Ultrasonic guided waves in bone system with degradation

**Dhawal R. Thakare** and **Prabhu Rajagopal**
*Centre for Nondestructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India; dhawal.thakare@gmail.com; prajagopal@iitm.ac.in*

**Pierre Belanger**
*Ecole de Technologie Superieure, Department of Mechanical Engineering, 1100 Rue Notre-Dame Ouest, Montréal, QC H3C 1K3, Canada; pierre.belanger@etsmtl.ca*

This paper investigates the feasibility of using ultrasonic guided waves for assessing cortical bone and hence aid in detecting conditions such as osteoporosis. Guided wave propagation in bone systems modeled as multilayered tubular structures consisting of anisotropic bone filled with viscous marrow and surrounded by tissue are studied using the Semi Analytical Finite Element (SAFE) method. Effects of changes to cortical bone thickness are investigated. An attempt is also made to consider bone anisotropy in the models. The results, validated by experiments with bone phantoms, show that material and geometric condition strongly impacts the velocity of guided waves supported in the bone system. Identification of optimal guided wave modes for practical assessment is also discussed.

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# I. INTRODUCTION

Quantitative ultrasound methods to assess the condition of the human bone have been widely studied in literature. Of these the more common, bulk ultrasonic wave based studies are limited to point scan measurements.[1-3] More recently guided ultrasonic waves have become of much interest to characterize bones in view of their ability for long range scanning from a single location.[4-7] Several studies have investigated the feasibility of guided waves, either in plates or tubes for assessing the condition of the human bone.[4-7] However, Lamb (plate) wave based studies fail to capture the tubular nature of the bone system. Most tubular based model studies on the other hand, also do not fully address the anisotropy of bone and the effect of tissue and marrow.

This paper investigates the use of guided ultrasonic waves in assessing degradation (mechanical or thickness changes) in human long bone, specifically the cortical bone. The representative bone models used in this paper account for the anisotropy of the bone (both orthotropic and transversely isotropic models have been used), the viscoelasticity of the bone marrow and the presence of soft tissue. In order to assess the capability of guided waves in doing so, the dispersion characteristics of the bone models are found using the Semi Analytical Finite Element (SAFE) method. This method has been illustrated further in Section II.C. One particular bone model has also been validated using experimental studies performed on bone phantoms (discussed further in Section II.A). The results show that the cylindrical guided wave modes of the bone system, F(1,6) and L(0,3) are promising for assessing the condition of the bone in presence of soft tissue and bone marrow.

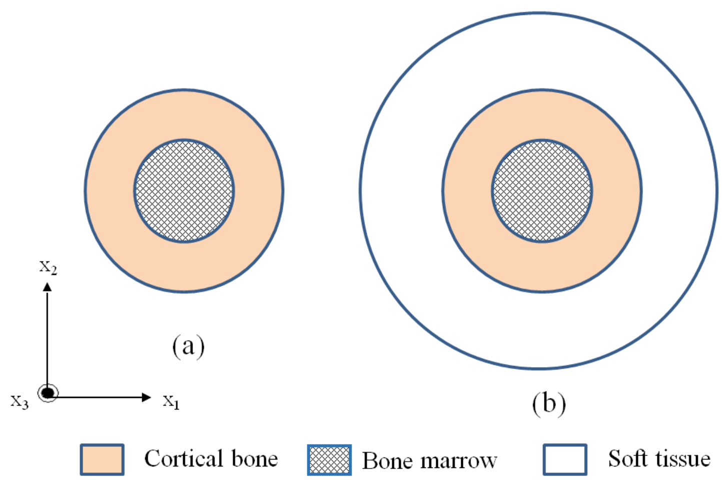


Figure 1: Illustration of (a) Model 1 -Cortical bone (*inner radius 7mm and 9mm with thicknesses of 3mm and 1mm respectively*) filled with marrow and (b) Model 2- Cortical bone additionally surrounded by tissue (*thickness 5mm*)

# II. MATERIALS AND METHODS

## A. Bone models

This paper addresses two representative bone models called Model 1 and Model 2 for brevity. Model 1 involves a transversely isotropic tubular cortical shell filled with a bone marrow as shown in Figure 1(a). In order to model dimensional degradation, two thicknesses of the cortical shell namely 3 mm and 1 mm have been used with the outer diameter fixed at 20 mm. The material properties for this bone model are similar to the bone phantoms obtained from Sawbones, Pacific Research Laboratories, Inc., Vashon, WA.[8] These bone phantoms are fourth-generation composite cylinders having properties closer to values measured for the natural bones.[9] In order to mimic the bone marrow, the composite cylinders were filled with shore A-25 elastomer. The bone phantom was 250 mm in length with the outer diameter being 20 mm and cortex thicknesses of 3 mm and 1 mm. The material properties for both the composite bone and the bone marrow have been shown in Table 1. The cortical shell has been assumed to be transversely isotropic while the bone marrow has been assumed to be a non-viscous isotropic medium (due to lack of sufficient data on the elastomeric properties).

Table 1. Material properties for the components of Model 1 considered.

| Component of the bone system | Longitudinal Tensile Modulus | Transverse tensile Modulus | Transverse Shear Modulus | Longitudinal Shear Modulus | Poisson ratio | Density ($kg/m^3$) |
|---|---|---|---|---|---|---|
| Cortical bone | 16 GPa | 10 GPa | 3.5 GPa | 5 GPa | 0.26 | 1640 |
| Bone Marrow | 3.5 MPa | - | - | - | 0.4 | 1026 |

Model 2, in addition to bone anisotropy, also consider the effects of soft tissue and viscous bone marrow on guided wave propagation in dimensionally degraded cortical bones. Model 2 (illustrated in Figure 1(b)) involves a circular cortical shell of outer diameter of 20 mm, filled with viscous bone marrow and coated with a layer of soft tissue. The cortex has been assumed to be orthotropic in nature while the soft tissue is assumed to be isotropic. The bone marrow with a Bulk's Modulus of 2.2 GPa, viscosity of 37 cP and density of 1000 $kg/m^3$ has been modeled as an equivalent viscoelastic solid. The material properties[10] used for Model 2 have been shown in Table 2. The cortex has been modeled at three thicknesses of 3 mm, 2 mm and 1 mm.

Table 2. Material properties for the components of Model 2 considered.

| Component of the bone system | $C_{11}$ (GPa) | $C_{12}$ (GPa) | $C_{13}$ (GPa) | $C_{22}$ (GPa) | $C_{23}$ (GPa) | $C_{33}$ (GPa) | $C_{44}$ (GPa) | $C_{55}$ (GPa) | $C_{66}$ (GPa) | Density ($kg/m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Cortical bone | 18 | 9.98 | 10.1 | 20.2 | 10.7 | 27.6 | 6.23 | 5.61 | 4.52 | 2300 |
| Soft Tissue | 17 | 12.8 | 12.8 | 17 | 12.8 | 17 | 2.1 | 2.1 | 2.1 | 1250 |

## B. Experimental studies on bone phantoms

Phantoms of cortical bone were acquired from Sawbones, Pacific Research Laboratories, Inc., Vashon, WA.[8] The dimensions were chosen to be similar to the middle section of a typical cortical bone like the radius. The experimental setup comprised of two ultrasonic transducers, either Shear (for instance, Olympus V1548, central frequency of 100 kHz and diameter of 31.75mm) or Longitudinal (for instance, Olympus X1020, central frequency of 100 kHz and diameter of 45mm). The shear transducer was used to excite modes with a dominant in-plane surface excitability whereas the longitudinal transducer was used to excite modes with a dominant axial excitability. The ultrasonic probe was maintained in position using a clamp and commercial gel was used as couplant. In order to scan a range of frequencies, the input signal was set to a 3 cycle Hanning windowed tone burst with a center frequency between 50 and 200 kHz as appropriate. The experimental velocities were extracted using the Short-Time Fourier Transform (STFT)[11,]. The STFT was used to provide a time amplitude representation as a function of frequency. The time-of-flight of each mode was then extracted manually as a function of frequency. The experimental velocities were obtained only for frequency ranges of 100 to 120 kHz and 180 to 200 kHz in steps of 10 kHz.

### C. Semi Analytical Finite Element (SAFE) method

Recent studies[12,13] have made the procedure for SAFE accessible by allowing it to be executed through commercial FE routines. The SAFE[23,24] model assumes the geometry to be uniform in the axial or the wave propagation direction, and hence the wave field to be harmonic in the axial direction. The governing equations are represented in the form of an eigenvalue problem with appropriate boundary conditions such that the eigen-solutions to the equation yields wave numbers. The eigenvalue equation in commercial FE softwares like COMSOL[14], have the general form as shown in Eq. (1).

$$\nabla.(\mathrm{c}\nabla\mathrm{U} + \alpha\mathrm{U} - \gamma) - \beta\nabla\mathrm{U} - \alpha\mathrm{U} + \lambda\mathrm{d}_{\mathrm{a}}U = 0 \tag{1}$$

The coefficients c, α & β depends on the material stiffness properties, α is a function of mass density and angular frequency, $d_a$ depends on stiffness properties, mass density and angular frequency and γ, λ are null in our case. All matrix coefficients used in Eq. (1) are given by Predoi et al (2007)[13]. The actual possible modes are obtained based on higher power flow[12] which represents the propagating mode guided along the cortex. The SAFE method is highly advantageous for complex materials like the bone because it allows for easy incorporation of features like anisotropy, viscoelasticity, multiple layered media and irregular cross-section without major changes in the central formulation.

## III. RESULTS AND DISCUSSION

### A. Model 1: Experimental study on bone phantoms

Experiments as explained in Section II.B were conducted on bone phantoms and the experimental group velocities for the various modes were extracted. SAFE was used to calculate group velocity and phase velocity dispersion curves for Model 1 for both the cortical thicknesses of 3 mm and 1 mm. The experimentally obtained mode velocities are compared against the SAFE predictions in Figure 2 below. The results show that simulation results are in good agreement with SAFE results with some degree of error. The errors might be due to inherent assumptions in SAFE method, random errors during experimental studies or inaccuracy in measured phantom properties.

### B. Model 2: SAFE of Orthotropic cortical bone with presence of soft tissue

Model 1 involved an anisotropic bone, but neglected the effects of the presence of soft tissue and the viscoelasticity of the bone marrow. These effects are accounted through Model 2 which investigates the effect of dimensional degradation on wave propagation in an orthotropic cortical bone filled with a viscous marrow and coated with a soft tissue. The SAFE results for phase velocity dispersion for Model are shown in Figure 3. The results show that the cylindrical guided wave modes of the bone system, L(0,3) and F(1,6) show an average velocity difference over 100 m/s in thinned bones as compared to the base bone system of 3mm thickness.

### C. Effect of Mechanical Degradation

Previous studies[15,16] performed by the authors have considered mechanical degradation by including models of cortical bone with varying levels of degradation as well as non-uniform levels across the cross-section. The results showed that L(0,3) and F(1,6) are suitable modes for assessing the mechanical condition similar to the results reported here.

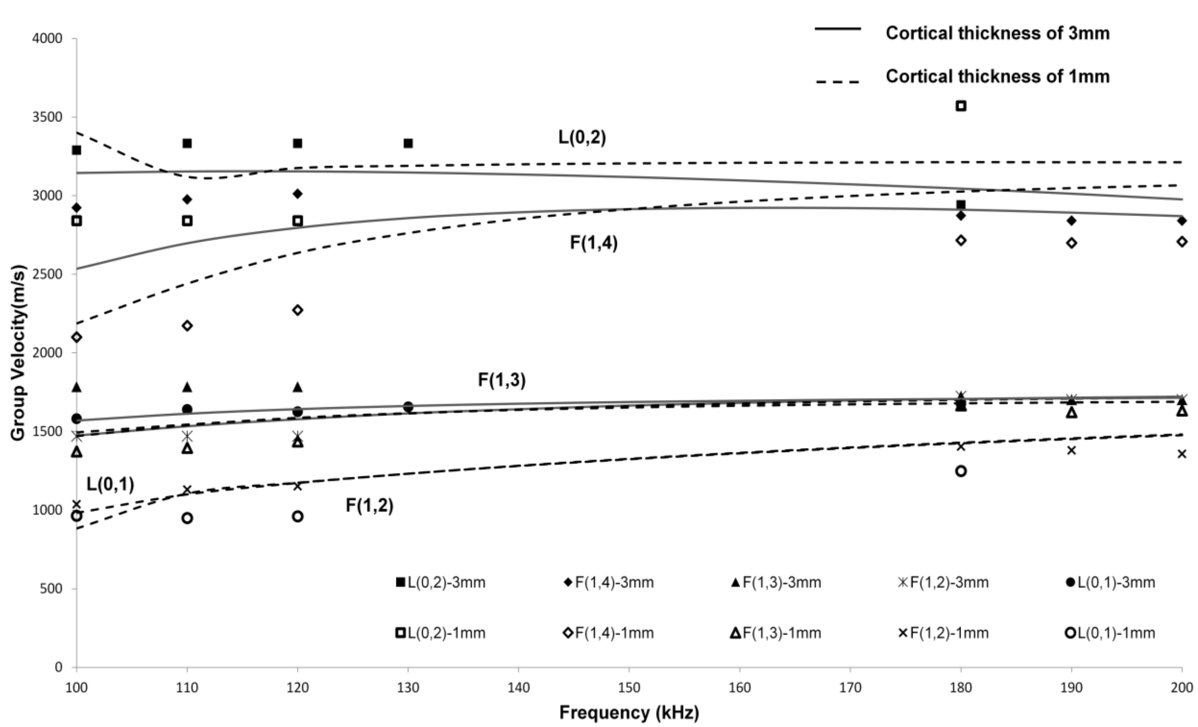


Figure 2: Group velocity dispersion curves from SAFE analysis (solid & dashed) and experimental studies (dots) for Model 1 (Cortex of thicknesses of 3mm and 1mm filled with marrow)

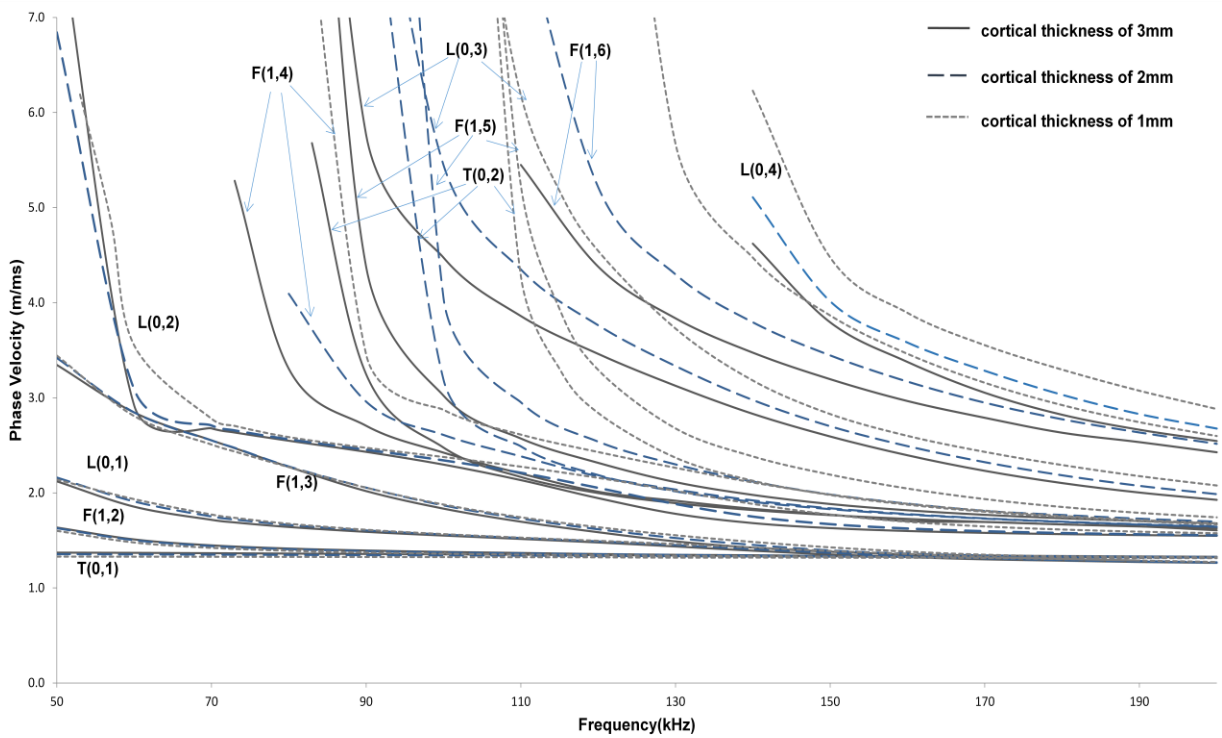


Figure 3: Phase velocity dispersion curves from SAFE analysis for Model 2 (Cortex of thicknesses of 3mm, 2mm and 1mm filled with marrow and coated with soft tissue)

## IV. CONCLUSION

This paper studies guided wave propagation in a realistic bone system with degradation. The model included bone anisotropy, a coating of soft tissue and a viscous bone marrow. The simulation approach was validated using experimental studies on bone phantoms. The studies show that velocity of higher order guided wave modes, namely L(0,3) and F(1,6) are affected strongly by dimensional degradation.

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