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Efficient Phase Velocity Estimation of Ultrasonic Guided Wave Propagating in Cortical Bone Using Adaptive Beamforming Technique

適応型ビームフォーミングを用いた皮質骨を伝搬する超音波ガイド波の位相速度推定方法

Shigeaki Okumura[1‡], Vu-Hieu Nguyen[2], Hirofumi Taki[3], and Toru Sato[1] ([1]Grad. School Inform., Kyoto Univ.; [2] Université Paris-Est; [3]Grad. School Biomed. Eng., Tohoku Univ.)

奥村成皓 [1‡], Vu-Hieu Nguyen[2], 瀧宏文 [3], 佐藤亨 [1] ([1] 京大院 情, [2]Université Paris-Est, [3] 東北大院 医工)

1. Introduction

The daily evaluation of bone quality is desirable for the health monitoring and disease prevention. The ultrasound axial transmission technique is commonly used for this purpose [1]. This technique analyzes ultrasonic guided wave propagation in cortical long bones.

Minozio et al. [1] have proposed a technique that estimates the phase velocity of the Lamb wave, an ultrasonic guided wave propagating in a thin plate. The method requires multiple transmitters and relatively large computational complexity. In this study, we propose a techique that estimates the phase velocities using a single transmitter with lower computational complexity.

The Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) is an adaptive beamforming technique that estimates the direction of arrival without requiring peak search [2]. The Unitary ESPRIT (UESPRIT) is a modified ESPRIT that has lower computational complexity. In this study, we modify the UESPIT for phase velocity estimation of Lamb wave in elastic plates.

The Lamb wave is constructed from multiple symmetric and anti-symmetric modes. However, conventional techniques estimate distributed phase velocities in frequency-phase velocity domain and do not clusterize the estimated phase velocities that arise from the same mode into the same cluster. This clusterization makes it easier to estimate the elastic parameters of bone. Therefore, we also propose a clusterization technique [3].

2. Materials and Methods

1.1 Lamb wave phase velocity estimation technique

Fig. 1 shows the system model. We use a linear array probe that has a transmitter and N receivers. To simplify, we introduce the modified ESPRIT method here. The Fourier transformed received signal vector at the linear array $\mathbf{X}(f)$ is expressed by following equation

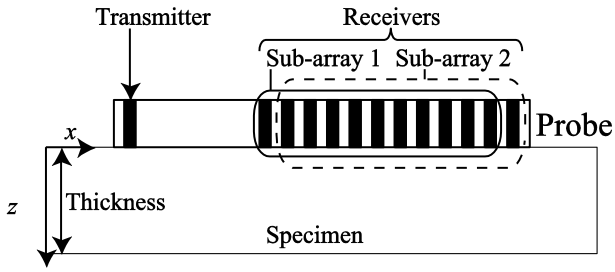

Fig. 1 System model

$$\mathbf{X}(f) = \mathbf{A}(f)\mathbf{S}(f) = [\mathbf{a}(f,1)\cdots\mathbf{a}(f,M)][S_1(f)\cdots S_M(f)]^{\mathrm{T}}, \quad (1)$$

$$\mathbf{a}(f,m) = [\exp\{\mathrm{j}\phi_1(f,m)\}\cdots\exp\{\mathrm{j}\phi_N(f,m)\}]^{\mathrm{T}}, \quad (2)$$

$$\phi_n(f,m) = -2\pi fnd / c_{\mathrm{p}}(f,m), \quad (3)$$

where m is the mode number, M is the number of modes appearing in the received signal, $S_m(f)$ is the spectrum of the m-th mode of the Lamb wave, n is the receiver number, d is the pitch of the receiver, and c_{p} is the phase velocity.

Here, let us define matrices $\mathbf{J}_1$ and $\mathbf{J}_2$, which select the sub-array signals 1 and 2, respectively, i.e., the received signal vector at sub-array k = 1,2 , $\mathbf{X}_k(f)$, is given by $\mathbf{J}_k\mathbf{X}(f)$. Between $\mathbf{J}_1$ and $\mathbf{J}_2$, the following relations is obtained:

$$\mathbf{J}_1\mathbf{A}\mathbf{\Phi} = \mathbf{J}_2\mathbf{A}, \quad (4)$$

$$\mathbf{\Phi} = \mathrm{diag}[\exp(\mathrm{j}\phi_1)\cdots\exp(\mathrm{j}\phi_M)]. \quad (5)$$

Because all the information about the phase velocity of each mode is included in $\mathbf{\Phi}$, the ESPRIT estimates $\mathbf{\Phi}$ using the eigenvalue of the covariance matrix given by $\mathbf{X}(f)\mathbf{X}^{\mathrm{H}}(f)$.

The basics of the UESPRIT are equivalent to those of the original ESPRIT. The USEPRIT employs the unitary transform to reduce the computational complexity of the method. The unitary transform is employed for the transition from complex to real signal processing.

1.2 Phase velocity clustering technique

The UESPRIT estimates the phase velocities of multiple modes of the Lamb wave at each frequency. To clusterize estimated velocities, we need to connect the velocities that arise from the same mode.

At two adjesent frequencies, we first predict a phase velocity at higher frequency using estimated phase velocity and its derivative at lower frequency in f-c_p domain. We next clusterize the estimated phase velocity at higher frequency that has smallest difference between predicted and estimated phase velocity into the same cluster.

1.3 Experimental setting

To evaluate the proposed method, we used a copper plate specimen. In this model, we did not consider attenuation. Fig. 2 shows the experimental setup. The linear array probe is attached to the 2.0-mm thick copper plate. The center frequency is 2.0 MHz. We use 25 receivers with d = 0.75 mm for the proposed test.

3. Results

Fig. 3 shows the results obtained by using the two-dimensional Fourier transform. The solid lines show the theoretical curves of phase velocities. The color map shows the normalized intensity. The 2D-FFT method failed to estimate the slower phase velocity at higher frequency.

Fig. 4 presents the results of the proposed method. The estimated velocities show a good match with the theoretical curves. The color of the legends shows the clusters. The method succeeded in classifying the estimated phase velocities that should arise from the same mode into the same cluster. The calculation time of the proposed method is 0.11 sec using MATLAB with an Intel® core i7 central processing unit.

4. Conclusion

We propose a new technique to estimate the phase velocity of the Lamb wave and to clusterize the estimated phase velocities. The estimated phase velocities show a good match with the theoretical curves in the experimental result, and the clustering result is accurate. The result shows high potential for bone quality assessment with a low computational complexity.

Acknowledgment
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Fig. 2 Experimental setup.

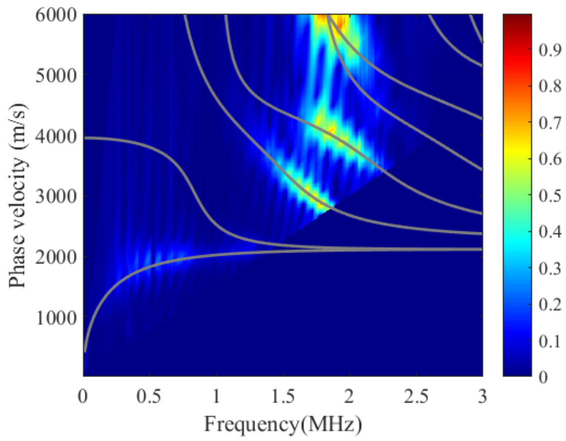

Fig. 3 Results of two-dimensional Fourier transform. Solid lines shows the theoretical phase velocities of Lamb wave.

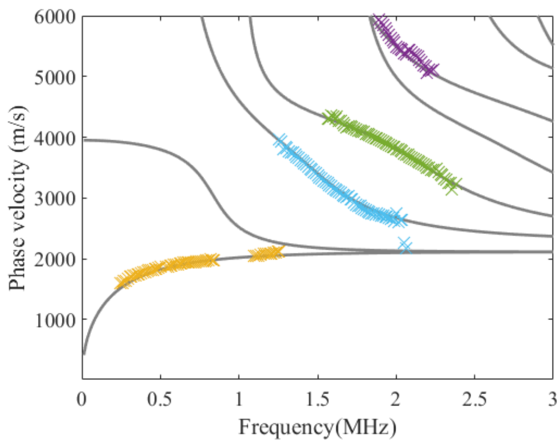

Fig. 4 Results of the proposed method and theoretical curves. Solid lines shows the theoretical phase velocities of Lamb wave.