1P5-17

Wavenumber Estimation of an Ultrasonic Guided Wave Propagating in Cortical Bone Using an Adaptive Signal Processing Technique with Information Theoretic Criteria

適応型信号処理と情報量基準を用いた皮質骨を伝搬する超音波ガイド波の波数推定

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 screening of cortical bone quality is important for the early detection of osteoporosis. Recently, the ultrasound axial transmission (AT) has attracted strong attention [1]. AT is a technique that reveals the properties of specimen by analyzing the ultrasonic guided wave, which is called the Lamb wave, propagating in the cortical bone. The wavenumber of the Lamb wave reflects the properties of a specimen. Estimation of the wavenumbers of the Lamb wave is thus important.

Several studies have been conducted to estimate the wavenumber of the Lamb wave. Our group reported the high-resolution wavenumber estimation for AT employing the Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) algorithm [2]. The algorithm requires the estimation of the number of propagation modes that exist at the measurement frequency. We make this estimation by evaluating the correspondences between results with different aperture size of probe. However, the use of a smaller aperture deteriorates the resolution. Thus, in the present study, we propose an algorithm that estimates the wavenumbers without sacrificing the aperture size of the probe.

We estimate the number of the propagation modes which exist at the measurement frequency by using information theoretic criteria [3]. The method is known to estimate the number of signal sources in the received signal for the ESPRIT algorithm. However, the method is not optimized for AT and it causes false estimates. Thus, we propose a technique that removes the false estimated wavenumbers by focusing on the characteristic of Lamb wave[2].

2. Materials and Methods

1.1 Basics of the ESPRIT algorithm

Figure 1 shows the system model. We use a linear array probe that has a single transmitter and N equally-spaced receivers. Here, we briefly explain the basics of ESPRIT algorithm.

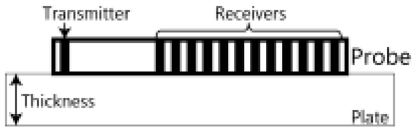

Fig. 1 System model

The ESPRIT algorithm estimates multiple propagation waves through eigenvalue decomposition of the covariance matrix. The covariance matrix is estimated by situating the full-array into sub-arrays and averaging the covariance matrixes at sub-arrays. The matrix is given by following equation:

$$\mathbf{R}(f) = \frac{1}{D}\sum_{i=1}^{D}\mathbf{S}_i(f)\mathbf{S}_i^{\mathrm{H}}(f), \qquad (1)$$

where $\mathbf{S}_i$ is the signal vector at i-th subarray, $\mathbf{R}$ is the covariance matrix, $[]^{\mathrm{H}}$ denotes the Hermitian transpose, and D (= $N - N_{\mathrm{sub}} + 1$) is the number of covariance matrix averaging. N_{sub} is the sub-array size.

The number of the propagation mode, M, is conventionally estimated by using the eigenvalue with thresholding process because larger eigenvalues represents the received signals and lower eigenvalues correspond to the intensity of noise.

1.2 Proposed estimation technique of the number of propagating modes using information theoretic criteria

To estimate the number of propagation modes existing at the measurement frequency, we employ a method based on the information theoretic criteria [3, 4].

$$M(f) = \arg\min_{m}(g(m,f)), \qquad (2)$$

$$g(m,f) = -\log\left[\frac{\prod_{i=m+1}^{N} l_i^{1/(N-m)}}{\sum_{i=m+1}^{N} l_i/(N-m)}\right]^{(N-m)D} + \frac{1}{2}m(2N-m)\log D \quad, \qquad (3)$$

where g is the evaluation value of the covariance matrix, $M(f)$ is the estimated number of propagation mode, and l_i is the i-th eigenvalue of the covariance matrix. The number of modes corresponds to m that minimizes g.

As shown in Eq. (3), the first term of g is the ratio between geometric and arithmetic mean of the eigenvalues. Thus, with a large range of the eigenvalue, the estimation is unstable. To overcome this problem, the technique of adding the offset value to the eigenvalues has been reported [4]. The reported method adds the offset value by adding the quasi-noise matrix to the covariance matrix.

$$\mathbf{R}'(f) = \mathbf{R}(f) + \lambda_{\mathrm{d}}\mathbf{I}\,, \qquad (4)$$

where λ_{d} is the stabilization factor, and $\mathbf{R}'(f)$ is the modified covariance matrix, and $\mathbf{I}$ is the unit matrix.

The choice of the stabilization factor directly affects the performance of the technique. We thus propose a new method to determine the factor for wavenumber estimation of Lamb wave. $M(f)$ does not change drastically along f direction. Thus, we do not set the offset value independently along f direction, but set it by the following equation.

$$\lambda_{\mathrm{d}} = \eta \max_{f}[\mathrm{tr}\{\mathbf{R}(f)\}/N_{\mathrm{sub}}]\,, \qquad (5)$$

where tr{} denotes the trace of the matrix and η is the constant value.

1.3 Elimination of false wavenumber estimates

We finally remove the false wavenumbers estimates using the A0 mode wavenumber. The A0 mode has the highest wavenumber and is dominant in the lower frequency range. The ESPRIT algorithm can estimate the intensity of each mode. Thus the wavenumber with the highest intensity in the low frequency range corresponds to the A0 mode wavenumber.

In the frequency-wavenumber domain, the A0 mode wavenumber lineally increase with increasing frequency. Thus, we employ linear approximation and remove the wavenumber that is higher than the estimated line.

1.4 Simulation setting

We conduct a simulation to evaluate the proposed method. A linear array probe is attached to a 2.0-mm thick copper plate. The center frequency is 1.0 MHz. We use 16 receivers with 0.75 mm pitch. The peak spectrum density signal to noise ratio is 30 dB. We use $\eta = -50$ dB.

As the conventional method, we select the eigenvalues that are larger than one-hundredth of the maximum eigenvalue.

3. Results

Figure 2 shows the estimated wavenumbers of the Lamb wave. The root-mean-squared errors (RMSE) for the proposed method and conventional method are 74 rad/m and 831 rad/m, respectively. The proposed method succeeded in estimating the wavenumber accurately and eliminating the false estimates at wavenumber of around 8000 rad/m.

4. Conclusion

We proposed a new algorithm that estimates wavenumbers of the Lamb wave. The proposed method does not sacrifice the aperture size; i.e., resolution. The method estimated the number of propagation mode at each frequency and succeeded in estimating the wavenumber of Lamb wave accurately. The results demonstrate that the proposed algorithm has high potential for the assessment of bone quality.

Acknowledgment

This work was supported in part by a Grant-in-Aid for Scientific Research (A) (Grant No. 25249057) and a Grant-in-Aid for JSPS Fellows (Grant No. 15J05687).

References

1. J. G. Minonzio, M. Talmant, and P. Laugier: J. Acoust. Soc. Am. **127** (2010).
2. S. Okumura, V.-H. Nguyen, H. Taki, G. Haïat, S. Naili and T. Sato: Jpn. J. Appl. Phys. **55** (2016).
3. M. Wax and T. Kailath: IEEE Trans. Acoust., Speech, Signal Process., **33** (1985).
4. Z. Zuo, J. P. Hu, Z. P. Huang, and Y. M. Zhang: Proc. MATEC Web of Conferences, **44** (2016)

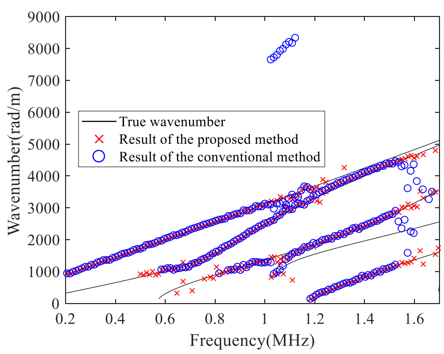

Fig. 2 Wavenumber estimation results of the proposed method and the conventional method (red cross marks and blue circles) and the true wavenumber (black lines).