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A Hilbert-Huang Transform based Time-of-flight method for shear wave elastography of thin layered media

SWEを薄板状媒質に適用するためのHilbert-Huang Transformに基づくTime-of-flight法

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1. Introduction

Ultrasound shear wave elastography (SWE) allows noninvasive and quantitative evaluation of mechanical properties of human soft tissues. Generally, shear wave velocity (C_S) can be estimated using time-of-flight (TOF) method if a medium is unbounded. And then, Young's modulus (E) is calculated directly from the estimated C_S, i.e., $E=3\rho C_S^2$ where ρ denotes density [1]. However, shear waves propagating through thin layered media (e.g., arterial wall, skin layer, or cornea) are so influenced by dispersion effects and multiple modes characterisics that Cs (=distance/travel time) can not be accurately estimated by the general TOF method. To overcome this limitation, Lamb-wave based dispersion analysis method has been recently proposed in [2]. This method, however, has some limitations: (i) It can not depict C_S or E distribution that can provide useful information to clinicians. (ii) Its result can be quite dependent on the thickness of the object being interrogated. Because most thin layered tissues have their irregular thickness, it is sometimes difficult to directly determine the thickness on B-mode images.

The multiple modes characteristics of Lamb waves make it difficult for the general TOF method to extract the travel time. In contrast, Hilbert-Huang Transform (HHT), firstly proposed by N. E. Haung [3], can extact the travel time of Lamb waves by dividing the multiple modes waves into several intrinsic mode functions [4].

In this work, we proposed a HHT-based TOF method, and performed a finite element analysis (FEA) to evaluate its feasibility of estimating C_S for thin layered media in ultrasound SWE applications.

2. Methods

2.1 Finite Element Analysis

Fig. 1 illustrates a thin layered model of the FEA with PZFlex® (Weidlinger Associates Inc.), a time domain FEA package. The model was assumed to be a linear elastic, homogeneous material. And C_L and C_T respectively denote the longitudinal wave velocity and the transverse wave velocity of the model. The perpendicularly or axially applied pressure generated shear waves to propagate in the lateral direction. After obtaining axial particle velocity data from the FEA, C_S was estimated using the two methods described below.

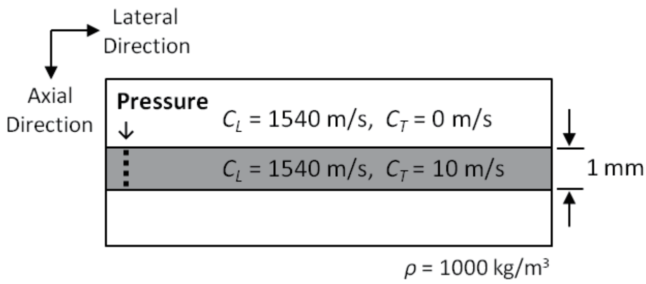

Fig. 1 Illustration of the FEA model

2.2 General TOF method

Because shear waves propagate in the lateral direction, we need to know the travel time (Δt) of the shear waves and the distance (Δd) between two reference pixels located at the same depth (i.e., the same axial distance) to estimate C_S (=$\Delta d/\Delta t$) at the center black-filled pixel as shown in **Fig. 2**. First, we designated the two reference pixels equally spaced from the interrogated pixel, and then calculated the travel time from the particle velocity data at the two reference pixels by performing a cross-correlation with respect to time. This procedure was repeated for the whole pixel area of the particle velocity data.

2.3 HHT-based TOF method

The shear waves in thin layered media propagate as guided waves, especially Lamb waves [2]. The significant features of Lamb waves are dispersion and multiple modes characteristics. HHT method divides multiple modes signal, which is nonlinear and nonstationary, into several intrinsic mode functions (IMF) by using empirical mode decompsition, and then performs Hibert trasnform [3]. This principle has also used in the field of nondestuctive evaluation especially for thin plate

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investigation, as described in [4]. In this work, after performing EMD, Hilbert trasnform was performed on the 1st IMF function. And then the general TOF method was used to estimate C_S.

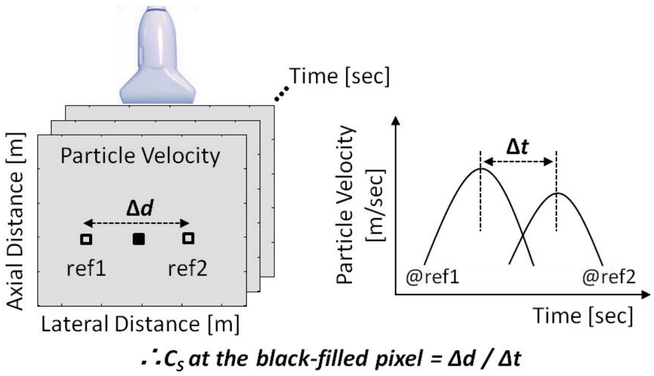

Fig. 2 Scheme of the general TOF method

3. Results and Discussion

Fig. 3 and **Fig. 4** show the C_S distributions estimated by the general TOF method and the proposed method, respectively. Both results were filtered with threshold above 15 m/s. C_{S_mean} that is the mean C_S in the dashed box was not equal to C_T (FEA set value = 10.0 m/s) in Fig. 1 and showed a non-uniform distribution, although the FEA model was assumed to be a homogeneous material. Even though some non-uniform area was also seen in the C_S distribution of Fig. 4, C_{S_mean} gave close agreement with the FEA set value.

Table I summarizes C_{S_mean} estimated by the two methods. The error between FEA set value and C_{S_mean} estimated by the general TOF method and the proposed method was 75% and 0.4%, respectively.

Table. I Comparsion of C_{S_mean} estimated by the two methods

	FEA set value (C_T)	General TOF	HHT-based TOF
C_{S_mean}	10.0 m/s	2.5 m/s	10.04 m/s
Error	-	75%	0.4%

4. Conclusion

In this work, we proposed and validated a HHT-based TOF method that can be applied to accurately estimate the shear wave velocity for thin layered media by performing a FEA study, while the general TOF method is suitable only for unbounded media. Future studies should focus on assessing the reproducibility of the proposed method under various conditions, as well as evaluating its clinical feasibility.

5. References

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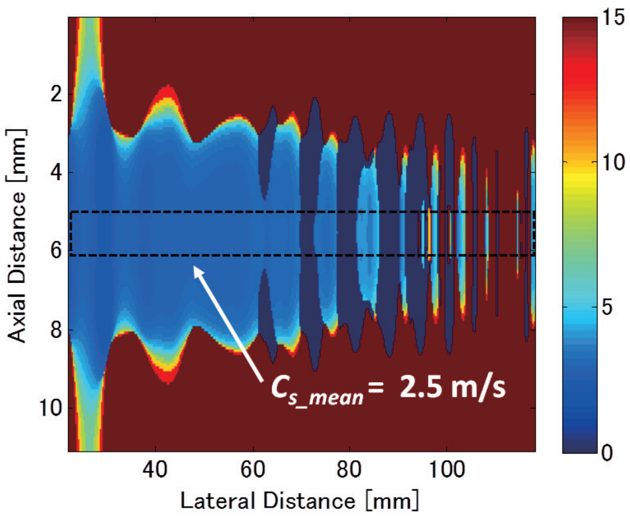

Fig. 3 C_S distribution of the general LTOF method

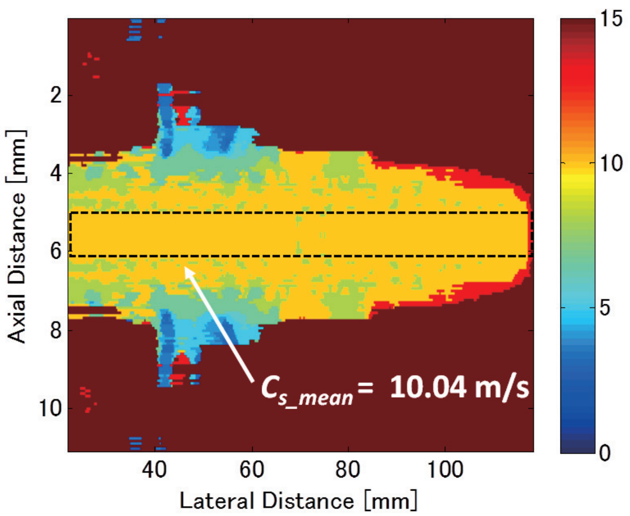

Fig. 4 C_S distribution of the proposed HHT-based TOF method