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Shear wave imaging using phase modulation component of harmonic distortion in continuous shear wave excitation

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1. Introduction

It is expected that the shear wave velocity is a quantitative parameter in tissue elasticity measurement as well as for mechanical characterization of the tissue [1, 2]. However, when continuous shear wave excitation is adopted in which the shear wave is excited by a vibrator which is attached on tissue surface, the quality of the image, such as resolution and the accuracy of the measurement, depend on both the frequency of the shear wave and its propagation characteristics. But the image quality is not sufficiently high in the conventional systems because high frequency shear wave cannot be introduced especially due to two reasons. First reason is that the amplitude of displacement which is caused by shear wave propagation decreases with the increase in frequency. Second reason is that the attenuation of shear wave increases with the increasing frequency.

We have proposed a novel method for estimating the velocity of the shear wave propagation inside the tissue by using continuous shear wave excitation method [3].

In this paper, we propose a method which can reconstruct spatial phase modulation component of shear wave propagation in order to obtain high resolution image of continuous shear wave excitation. Shear wave local velocity which is derived from the spatial differentiation of phase of complex displacement is adopted as an imaging parameter. A fine texture pattern of phase modulation component, which appears on the local velocity map, gives precise information of small amplitude phase modulation as well as non-linear characteristic of the medium. These parameters could be very useful for characterizing the non-linearity as well as the mechanical structure of the medium with high spatial resolution.

2. Local Velocity Estimation Using Up-Sampled RF correlation method

First, complex 2D displacement is calculated from the ultrasonic wave Doppler signal by using cross-correlation of the up-sampled RF signals. The complex displacement is then written as follows.

$$\xi(x,z) = |\xi(x,z)|\exp(j\theta(x,z)) \quad (1)$$

The phase differences in x and z direction is derived from the complex displacement as shown in the following equations.

$$\Delta\phi_x(x,z) = \arg[\xi^*(x+\Delta x,z)\xi(x,z)] \quad (2)$$
$$\Delta\phi_z(x,z) = \arg[\xi^*(x,z+\Delta z)\xi(x,z)] \quad (3)$$

Shear wavelength in x and z directions are estimated from equation (2) and (3).

$$\lambda_x(x,z) = (2\pi f_b \Delta x)/(f_b \Delta\phi_x(x,z)) \quad (4)$$
$$\lambda_z(x,z) = (2\pi f_b \Delta z)/(f_b \Delta\phi_z(x,z)) \quad (5)$$

Shear wave local velocity is obtained from the spatial differentiation of the vibration phase along the shear wave propagation direction.

$$V_L(x,z) = f_b\lambda_x(x,z)/(\sqrt{1+(\lambda_x(x,z)/\lambda_x(x,z))^2}) \quad (6)$$

When there is no phase modulation in the shear wave, the derived local velocity is equal to the shear wave velocity and the map becomes a shear wave velocity map. But in case if there is a presence of small phase modulation in the shear wave, fine texture like patterned wave-front of harmonic component is appeared in the local velocity map.

3. Reconstruction of phase modulation of harmonic component of the of shear wave

Now, let us consider the texture pattern when the shear wave has a phase modulation. We assume that small displacement, which is caused by shear wave propagation, is given by following equation,

$$\xi(\mathrm{r}) = \xi_o \exp(j(k_o \mathrm{r} + \varphi(\mathrm{r}))) \quad (7)$$

Where,

$$\varphi(\mathrm{r}) = \varphi_o \sin(k_1 \mathrm{r} + \theta) \quad (8)$$

In the above equation, ξ_o is the displacement amplitude, k_o is wave number of the fundamental shear wave, k_1 is the wave number of the distortion component and θ is the phase of the distorted

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component. From eq. (8), the differentiation of phase of the displacement in two dimension form can be obtained as,

$$\partial(k_o \mathbb{r} + \varphi(\mathbb{r})/\partial \mathbb{r} = k_o + k_1\varphi_o \cos(k_1 \mathbb{r} + \theta) \quad (9)$$

The local velocity is then estimated by the following equation,

$$V_L = 2\pi f_o/(k_1\varphi_o \cos(k_1 \mathbb{r} + \theta)) \quad (10)$$

For very small phase distortion of φ_o, we obtain

$$V_L \cong v - v((f_o/f_1)\varphi_o \cos(k_1 \mathbb{r} + \theta)) \quad (11)$$

If the displacement has harmonic phase distortion, the local velocity, which is estimated from spatial differentiation of the vibration phase, shows the same spatial modulation with that of the phase distortion.

4. Experimental result

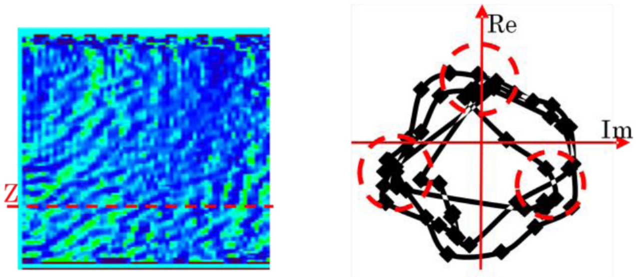
The texture pattern, which is appeared on the local velocity map, is evaluated for agar phantoms and in-vivo experiments. Fig.1 (a) shows the texture pattern of agar gel phantom with 1.5w% agar powder. The vibration frequency is 700Hz. In this map, the high local velocity position is illustrated by the bright color mapping. It is shown that fine texture pattern appears on the local velocity map. In order to evaluate the spatial phase modulation of complex displacement, complex displacement vector on the line Z is shown in fig.1 (b). The phase modulation of the complex displacement is especially seen at three regions on the vector map which are surrounded by the red dotted lines. Harmonic components of vibrator were measured by using accelerometer (Analog devices, MMA7361LC) attached to the vibrator head. In this experiment, a harmonic distortion of -47dB for 3rd order was observed.

Fig 2(a) is the local velocity mapping of the in-vivo experiment done at the upper arm for vibration frequency of 300 Hz. Fig 2(b) is the B mode image for the same imaging region.

5. Discussions

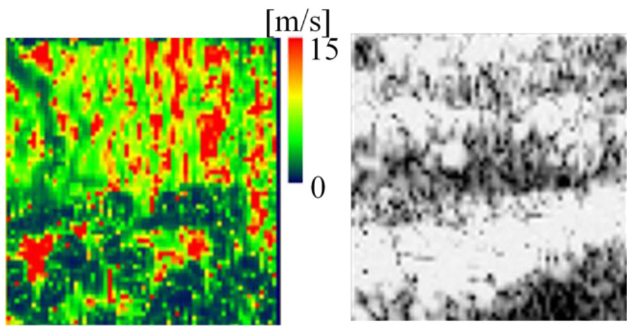
We have proposed a novel imaging method which uses the local velocity of the shear wave propagation to reconstruct the phase modulation component. The origin of phase modulation is not clear and so the further studies are necessary concerning about the texture pattern. However, the two reasons might be responsible for the occurrence of texture pattern on the local velocity map. First reason is that it comes from the harmonic distortion of vibrator itself. In our experiment, it is -47dB and is considered to be a bit small for explaining the generation of phase modulation. Second reason is the nonlinearity of medium. A lot of studies have been done for nonlinearity of elasticity of biological tissue and the imaging of harmonic component was already proposed [4]. We adopted the Fourier analysis to the complex displacement in order to extract the harmonic component. However, it is difficult to get high quality image from the data of short measurement time.

The proposed method is a method which can reconstruct a map of small phase modulation from the data of short time. It is achieved by the spatial differentiation of complex displacement map. This method is expected to be very useful for high resolution shear wave imaging as well as characterizing the non-linearity of the medium.



(a) (b)

Fig.1 Agar gel phantom experiment at 700Hz. Fig.1. (a) Enhanced texture pattern map of the local velocity by using proposed method. Fig.1.(b) Complex displacement vector map at position Z.



(a) (b)

Fig.2. In-vivo experiment (muscle of upper arm at 300Hz). Fig.2. (a) Local velocity map by proposed method. Fig.2. (b) B-mode Imaging

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