Ultrasonic Measurement of Strain Generated by Dual Acoustic Radiation Force for Evaluation of Acupuncture Therapy

Yoshitaka Odagiri, Hideyuki Hasegawa, Hiroshi Kanai
Graduate School of Engineering, Tohoku University,
Sendai 980-8579, Japan
E-mail: odagiri@us.ecei.tohoku.ac.jp

Abstract—Many studies have been carried out on the measurement of mechanical properties of tissues by applying an ultrasound-induced acoustic radiation force. To assess mechanical properties, strain of an object must be generated. However, use of only one radiation force is not sufficient because it also causes translational motion when the object is much harder than surrounding medium. In this study, two cyclic ultrasound radiation forces are applied to a phantom which mimics muscle from two opposite horizontal directions so that the object is cyclically compressed in the horizontal direction. As a result, the object is vertically expanded due to the incompressibility. The resultant vertical displacement is measured using ultrasound and laser vibrometer. Two concave ultrasonic transducers for actuation were both driven by sums of two continuous sinusoidal signals at two slightly different frequencies of 1 MHz and (1M+5) Hz. Displacement at the surface, which fluctuates at 5 Hz, was measured by the ultrasonic phased tracking method proposed by our group. The displacement was also measured with laser to validate ultrasonic measurement. Results indicated that the phantom was cyclically actuated with an amplitude of tenth of a few micrometers which well coincided with that measured with laser.

I. INTRODUCTION

Acupuncture is a kind of therapy by the insertion of very thin needles, from the skin surface in order to improve physiological functioning of the body. Figure 1 shows meridians in shoulders to alleviate the stiffness and appearance of acupuncture therapy. Acupuncture are over 2,000 years old and has developed based on the authority of experience. However, from the view point of the Western medicine, meridians, which the acupuncture depends on, do not correspond to nervus or blood circulation. Therefore, the acupuncture is an scientific controversial issue in the Western medicine. For this reason, quantitative evaluation of acupuncture therapy is important. Recently, some remote actuation methods based on acoustic radiation forces have been reported. Fatemi and Greenleaf proposed an imaging modality that uses the acoustic response of the object to a localized dynamic radiation force[1], [2]. The radiation force produces acoustic emission which is closely related to the mechanical frequency response of the medium. By measuring the acoustic emission with a hydrophone, hard inclusions in soft material may be experimentally detected. The spatial resolution in the depth direction corresponds to the size of the intersectional area.

However, as shown in Fig. 2(a), one acoustic radiation force does not generate strain in an object effectively because it also causes a change in the object’s position, which has zero spatial gradient in displacement. Especially when the elastic modulus of the object is far greater than that of the surrounding media, one acoustic radiation force may generate only a change in the position of the object[3]. In this study, as illustrated in Fig. 2(b), the strain on the face of an object is generated by placing it on a hard base. In addition, as illustrated in Fig. 2(c), for effective generation of strain in the object, two acoustic radiation forces respectively induced by two ultrasounds at frequencies \( f \) and \( f + \Delta f \) were applied to two different positions in the object from two different directions. In this study, the displacement generated by acoustic radiation forces was measured by the ultrasonic phased tracking method[4] and a laser Doppler velocimetry.

II. PRINCIPLE

As illustrated in Fig. 3, when the ultrasound propagates in a medium, a constant force is generated in the direction of propagation. This force is called as the acoustic radiation force[5]. The acoustic radiation pressure, \( P_R(t) \), is defined as the acoustic radiation force per unit area as follows:

\[
PR(t) = (1 + R^2)e(t),
\]

where \( R \) and \( e(t) \) are the pressure reflection coefficient and the energy density at the interface, respectively. In eq. (1), the
transmitted wave is assumed to be perfectly absorbed in the object. Using the densities, \( \rho_1 \) and \( \rho_2 \), and sound speeds, \( c_1 \) and \( c_2 \), of the medium and the object, the reflection coefficient, \( R \), and the energy density, \( e(t) \), are defined by

\[
R = \frac{z_2 - Z_1}{z_2 + Z_1} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \quad (2)
\]

\[
e(t) = \frac{1}{\rho_1 c_1^2} (p(t))^2 \quad (3)
\]

The energy density, \( e(t) \), of the incident wave is proportional to the square of the sound pressure, \( p(t) \), of the ultrasound beam. When two ultrasonic waves with the same sound pressure, \( p_0 \), at slightly different frequencies, \( f \) and \( f + \Delta f \), are crossed each other, an acoustic radiation pressure which fluctuates at the frequency difference, \( \Delta f \), is generated in the intersectional area. In this case, the sound pressure, \( p_{\text{sum}}(t) \), in the intersectional area is expressed as follows:

\[
p_{\text{sum}}(t) = p_0 \cos 2\pi ft + p_0 \cos 2\pi(f + \Delta f)t, \quad (4)
\]

For this case, the energy density, \( e(t) \), is expressed as follows:

\[
e(t) = \frac{1}{\rho_1 c_1^2} \left(p_{\text{sum}}(t)\right)^2 = \frac{1}{\rho_1 c_1^2} \left(p_0 \cos 2\pi ft + p_0 \cos 2\pi(f + \Delta f)t\right)^2
\]

\[
= \frac{p_0^2}{\rho_1 c_1^2} \left(1 + \cos 2\pi \Delta ft + \cos 2\pi(2f + \Delta ft)\right)
\]

\[
+ \frac{1}{2} \cos 4\pi ft + \frac{1}{2} \cos 4\pi(f + \Delta ft), \quad (5)
\]

From the second term of the right-hand side of eq. (5), it is found that the energy density, \( e(t) \), has a component at the frequency difference \( \Delta f \). With respect to the low-frequency component, the acoustic radiation pressure, \( P_R(t) \), acting on the interface is given by

\[
P_R(t) = (1 + R^2) \frac{p_0^2}{\rho_1 c_1^2} (1 + \cos 2\pi \Delta ft), \quad (6)
\]

where \( R \) is the pressure reflection coefficient on the surface of the object.

To improve the spatial resolution in measurements of the response of an object, an ultrasound correlation-based method, the ultrasonic phased tracking method, is used to measure the minute displacement, \( d(t) \), caused by the acoustic radiation force[6]. The accuracy in the displacement measurement by the phased tracking method was evaluated to be 0.2μm by basic experiments using a rubber plate[7], and influences of the focal position of the ultrasonic beam and the change in center frequency of RF echo due to the frequency-dependent attenuation in tissue on the measurement accuracy were also investigated.

III. EXPERIMENTAL SETUP

The measurement system is illustrated in Fig. 4. In order to measure the strain, we employed ultrasonic diagnostic equip-
displacement

Fig. 5: The results measured by laser Doppler velocimetry. (a) Maximal displacement generated by difference of $\Delta f$. (b) Displacement measured at frequency difference, 5 Hz.

ment (Toshiba SSH-160A) with a linear-type probe (center frequency: 3.75 MHz). The equipment was modified to detect the minute displacement of the object by the ultrasonic phased tracking method. Two concave ultrasonic transducers were driven by a sum of two continuous waves (CWs) at two slightly different frequencies of 1 MHz and 1 MHz+$\Delta f$ Hz. The resultant ultrasound beams were focused at 50 mm away from the surface of the transducer with a beam angle $\phi$. The displacements of the object, where the two acoustic radiation forces were applied, were measured by the ultrasonic phased tracking method [3]. The gel, which is phantom of muscle, for the practice of acupuncture was used as the object.

When CW ultrasound is employed for actuation, interference occurs between the CW ultrasound for actuation and the pulsed ultrasound for displacement measurement. In order to avoid this interference, an electrical switch to control the cessation of the CW ultrasound for actuation is used.

In this study, the amplitude of displacement was measured at each frequency difference, $\Delta f$. Then, the displacement of the object, in the case that one acoustic radiation force was applied, was measured by a laser Doppler velocimetry to check the actuation. When a laser Doppler velocimetry was used, reflection theet was pasted on the face of object to measure surface velocity. In this case, focal point of an acoustic radiation force was set at boundary with the reflection theet because the pressure reflection coefficient, $R$, changes when an acoustic radiation force is exerted on the face of reflection theet. Finally, regional strain was generated in the object efficiently using two focused ultrasonic transducers.

The maximal amplitude of displacement generated an acoustic radiation force at $\Delta f$ is shown in Fig. 5(a). When $\Delta f$ is 5 Hz, the amplitude was maximum, and rapidly decreases at higher frequencies. This is explained by the fact that the dynamic loss elastic modulus increases depending on frequency. In the frequency range from 1 Hz to 4 Hz, the displacement could not be measured because of the property of the laser Doppler. Figure 5(b) shows displacement measured at frequency difference, 5 Hz.

The displacement generated by using dual acoustic radiation forces was measured with ultrasound. In this experiment, the difference frequency, $\Delta f$, employed 5 Hz and angles, $\phi$ set to 25 degrees. Focal points of two transducers set at same position. Figures 6(a) shows the M-mode images of the object. Acoustic radiation pressures, $P_{R1}(t)$ and $P_{R2}(t)$, shown in Figs. 6(b) and 6(c) were moved in the same phase. Figure 6(d) shows the vibration velocity of the object obtained by the phased tracking method. By integrating the velocities, the displacement was obtained as shown in Fig. 6(e). The amplitude of the measured displacement was about 4.0 $\mu$m. From these results, using the proposed method, the regional strain was successfully generated and measured with ultrasound.

Displacement at each beam position is shown in Fig. 7. In this study, linear-type probe (center frequency: 3.75 MHz) was employed when displacement was measured by ultrasound.

IV. RESULTS

The maximal amplitude of displacement generated an acoustic radiation force at $\Delta f$ is shown in Fig. 5(a). When $\Delta f$ is 5 Hz, the amplitude was maximum, and rapidly decreases at higher frequencies. This is explained by the fact that the dynamic loss elastic modulus increases depending on frequency. In the frequency range from 1 Hz to 4 Hz, the displacement could not be measured because of the property of the laser Doppler. Figure 5(b) shows displacement measured at frequency difference, 5 Hz.

The displacement generated by using dual acoustic radiation forces was measured with ultrasound. In this experiment, the difference frequency, $\Delta f$, employed 5 Hz and angles, $\phi$ set to 25 degrees. Focal points of two transducers set at same position. Figures 6(a) shows the M-mode images of the object. Acoustic radiation pressures, $P_{R1}(t)$ and $P_{R2}(t)$, shown in Figs. 6(b) and 6(c) were moved in the same phase. Figure 6(d) shows the vibration velocity of the object obtained by the phased tracking method. By integrating the velocities, the displacement was obtained as shown in Fig. 6(e). The amplitude of the measured displacement was about 4.0 $\mu$m. From these results, using the proposed method, the regional strain was successfully generated and measured with ultrasound.

Displacement at each beam position is shown in Fig. 7. In this study, linear-type probe (center frequency: 3.75 MHz) was employed when displacement was measured by ultrasound.
Therefore, 16 positions can measure at one ultrasonic measurement. Displacement, when two focal points set at the same position, is shown in Fig. 7(a). Amplitude of displacement is higher in the vicinity of overlapping focal point than other position. Displacement, when distance of focal point set to 10 mm, is shown in Fig. 7(b). Displacement are more widely distributed than that Fig. 7(a). this shows that force such as pinch was applied.

V. Conclusion

In this paper, the displacement generated by acoustic radiation force was measured by ultrasonic probe and the laser Doppler velocimetry, and these results was same order, µm. It was shown that strain could be measured by using the ultrasonic phased tracking method. In addition, it was shown that regional strain was generated on the object using two focused ultrasonic transducers. These results show a potential of the proposed method for generation of the regional strain on the muscle.

References