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Frequency Characteristics of Vibration Generated by Dual Acoustic Radiation Force for Estimating Viscoelastic Properties of Biological Tissues

組織粘弾性特性推定のための双方向超音波加振による対象物振動周波数特性に関する検討

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1. Introduction

It is well known that progression of a lesion is accompanied with changes in hardness of biological tissues. Therefore, it would be important to measure the elasticity of living tissues for early detection and quantitative diagnosis of disorder in living tissues.[1)]

Using the dual acoustic radiation force by continuous sinusoidal ultrasonic waves, the sample is vibrated at an arbitrary frequency. Our purpose is to estimate viscoelasticity of the biological tissues by analyzing the displacement of the vibrating sample. In the present study, we measured the frequency dependence of the displacement on three phantoms, and evaluated their viscoelasticity values using the Maxwell model.

2. Materials and Method

The irradiated ultrasonic wave generates an acoustic radiation force in the traveling direction with respect to the reflector and the sound absorber.[2)] In the present study, we prepared an ultrasonic signal having frequency components of f_0 and ($f_0+\Delta f$), and applied it to the two same transducers. Thus, we used exactly the same acoustic radiation forces. The acoustic radiation force $P_R(z,t)$ is given by

$$P_R(z,t) \approx \frac{\alpha p_0^2}{\rho_2 c_2^2} e^{-2\alpha \cdot z}(1+\cos 2\pi \Delta f t), \qquad (1)$$

where α, ρ_2, c_2 and p_0 are attenuation coefficient, density, sound speed of the sample and sound pressure at the sample surface (z = 0), respectively.[3)]

As shown in **Fig. 1**, when the two transducers are installed obliquely to the surface of the sample, a force is generated locally in an oblique direction by one of the transducers. When the two acoustic forces are crossed each other, an acoustic pressure of the frequency Δf is generated in the intersectional region. Forces to synchronizedly push the surface of the sample from both sides and to perpendicularly push the surface of the sample are generated by using two transducers. Therefore, the periodic strain is generated with the frequency Δf in the vertical direction.[4)]

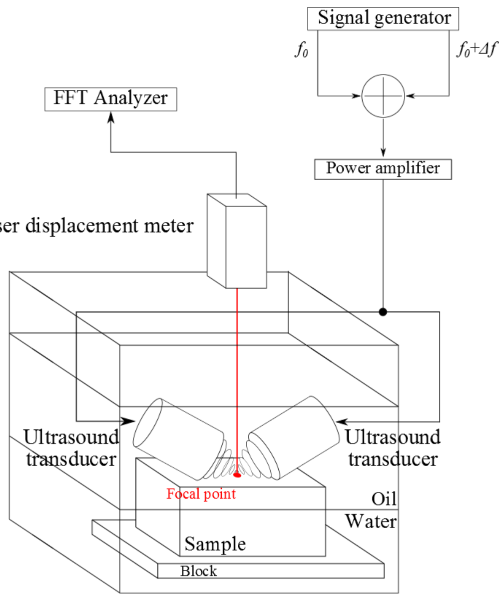

Fig. 1. Experimental setting employed in the present study.

We employed two point-focus transducers with a center frequency of 1 MHz, a diameter of 50 mm, and a focal length of 60 mm. The two transducers were installed so that their focal points were intersecting on surface of the sample.

We performed the ultrasonic vibration test by fixing the signal f_0 to 1 MHz and changing Δf from 20 to 2000 Hz. By observing the displacement generated on the surface of the sample with a laser displacement meter (LK-G80; KEYENCE Corp.) with a resolution of 0.2 μm, we investigated the frequency characteristics of sample displacement caused by dual acoustic radiation force. We analyzed the frequency power spectrum by inputting the measured displacement waveforms to the FFT analyzer (CF-940; ONO SOKKI Corp.) for each vibration frequency Δf. The power spectra averaged 8 times by the FFT analyzer were acquired 30 times.

The phantoms simulating biological soft

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tissues were prepared by mixing graphite at a ratio of 2% to urethane resin. Three phantoms with different hardness were prepared using gels (H0-100, H5-100, H15-100, Exile Corp.) whose Asker-C hardness values are 0, 5, and 15, respectively. Using 3 types of phantoms with different hardness, we measured and discussed the difference of the frequency characteristics.

3. Result and Discussion

The average value of the displacement and the standard deviation are shown in **Fig. 2**. In each phantom, the displacement decreased with a slope of -20dB/decade in the frequency range of 20-200 Hz as the vibration frequency increased. On the other hand, the displacement became constant in the frequency range of 700-2000 Hz. It was also confirmed that the frequency at which the displacement became constant was higher as the phantom became harder.

We considered the results with the Maxwell model which is one of the typical viscoelastic models as shown in **Fig. 3**. The spectrum $H(\omega)$ in Fig. 3 shows the transfer function when the input is the dynamic pressure and the output is the strain. According to Eq. (1), there is no frequency dependence of the acoustic radiation pressure which corresponds to the dynamic pressure, and the input of $H(\omega)$ is independent of the frequency. Thus, the frequency characteristics of the strain should be the same as $H(\omega)$. Strain is also linearly related to the displacement. Therefore, the result obtained in Fig. 2 should follow the theoretical graph of Maxwell model shown in Fig. 3.

The ratio of the elasticity G to the viscosity η was calculated for each phantom by fitting the result of the frequency characteristics in Fig. 2 to the inflection point of the Maxwell model. The ratio G/η [s^{-1}] was estimated as 1673, 2373, and 4938 for Hardness0, Hardness5, and Hardness15, respectively. The harder the phantom, the elasticity G becomes large. Thus, these estimated results of G/η should be reasonable. Accordingly, it was shown that the viscoelasticity of the phantom can be relatively evaluated by vibrating the phantom using ultrasonic waves with different frequencies and observing the response.

4. Conclusion

We generated periodic displacement on the surface of phantom simulating living soft tissues by irradiating ultrasound generated by adding two continuous sinusoidal waves with slightly different frequencies from two directions. The generated displacement was measured with the laser displacement meter. Frequency characteristics of the displacement were investigated by changing the vibration frequency Δf. It was confirmed that the frequency characteristics of the displacement were different depending on the hardness of the phantom. The ratio of the elasticity to the viscosity of the phantom was estimated from the frequency characteristics.

Currently, vibrations at lower frequency below 20 Hz cause the large error in the measurement. Thus, we employed frequency components above 20 Hz in the present study. If we can acquire lower frequency data, we can further consider the application model.

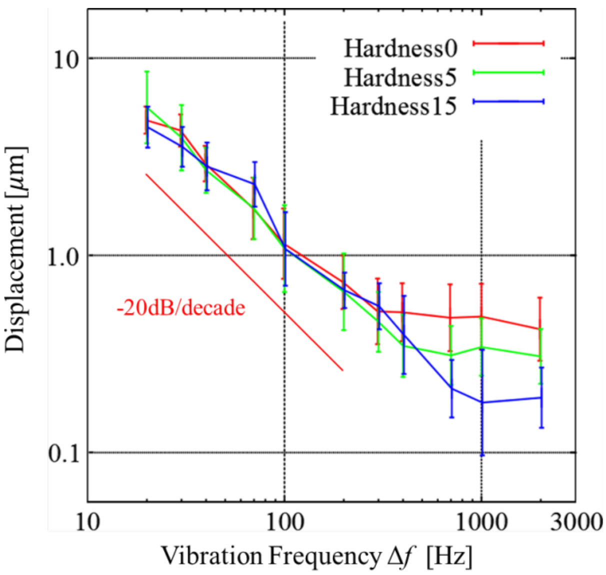

Fig. 2. Frequency characteristics of displacement for phantoms with different hardness.

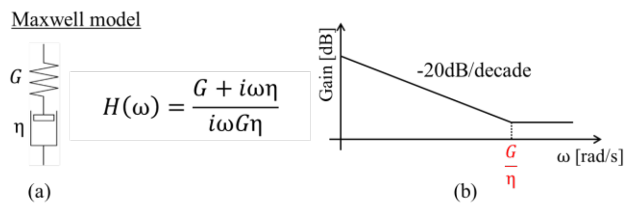

Fig. 3. Features of viscoelastic tissues assuming Maxwell model. (a) Elements of Maxwell model. (b) Frequency characteristics of the strain.

Reference

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