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Surface deformation of a tissue phantom using an airborne concave ultrasound transducer

凹面型空中超音波振動子による生体ファントムの変形

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1. Introduction

Acoustic radiation force is static force acting at a boundary between two media generated by acoustic nonlinear phenomenon. Acoustic radiation force has been applied to various fields such as medical and industrial fields. With the developments of virtual reality, augmented reality, and holography technologies, noncontact tactile feedback systems in air are required. Hoshi et al. reported tactile feedback using airborne ultrasound [1]. Tactile sense on fingertips can be induced by acoustic radiation force using ultrasound array transducers, and the tactile was evaluated qualitatively. In this study, surface deformation of a tissue phantom by acoustic radiation force was measured quantitatively using an airborne transducer, and the relationship between the acoustic field and the surface profile was investigated.

2. Ultrasound transducer and acoustic field

Airborne high-intensity ultrasound is required for tactile feedback systems, and we employed an ultrasound transducer with a hemispherical vibrating plate to generate focused ultrasound. **Fig. 1** shows the configuration of the ultrasound transducer. The inner and outer diameters of the hemispherical plate are 55 and 61 mm, respectively. A bolt-clamped Langevin transducer (BLT, HEC-3028P2BF, Honda Denshi) was attached to a stepped horn (length: 90 mm; tip diameter: 15 mm; transformation ratio: 1.7) to increase the vibrational amplitude. The hemispherical plate was attached to the tip of the horn by tightening a screw. The one-wavelength longitudinal resonance vibration mode was generated in the axial direction of the transducer at 27.5 kHz.

The vibrational distribution was measured using a laser Doppler vibrometer (LDV, NLV-2500, Polytec). The measurement area 40×40 mm^2 was scanned on the inner surface of the vibrating plate, and the vibrational displacement amplitude in z direction was measured. **Fig. 2** shows the vibrational displacement amplitude distribution of the vibrating plate at the resonance frequency of 27.5 kHz. The vibration amplitude was normalized by maximum value. The longitudinal vibration of the BLT and the horn was converted to the axisymmetric concentric flexural vibration on the vibrating plate (two nodal circles appeared in the measurement area). The maximum vibration displacement amplitude at the bottom of the hemispherical plate was 11.2 µm when the input voltage amplitude was 180 V_{pp}.

The sound pressure distribution was measured using a probe microphone (Type 4182, Bruel & Kjaer). **Fig. 3(a)** shows the result in the measurement area of 30×60 mm^2 in y-z plane at x = 30.5 mm (on the sound axis). The result was normalized by maximum value. When the input voltage amplitude was 180 V_{pp}, the maximum sound pressure amplitude at the focal point on the sound axis ((x, y, z) = (30.5, 30.5, 39 mm)) was 4.1 kPa. The sound pressure distribution in x-y plane at the focal point (z = 39 mm) was shown in **Fig. 3(b)**. The concentric cylindrical wave propagated in z direction (axial direction), and the wavelength in the radial direction corresponded approximately to that of the flexural vibration on the hemispherical plate.

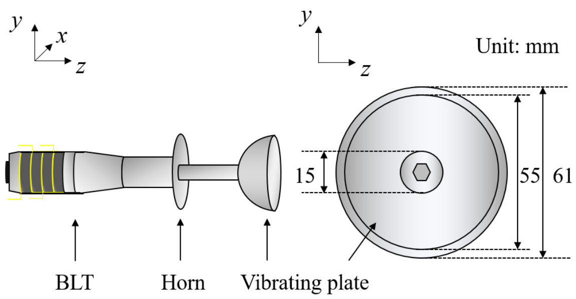

Fig. 1 Ultrasound transducer with a hemispherical vibrating plate.

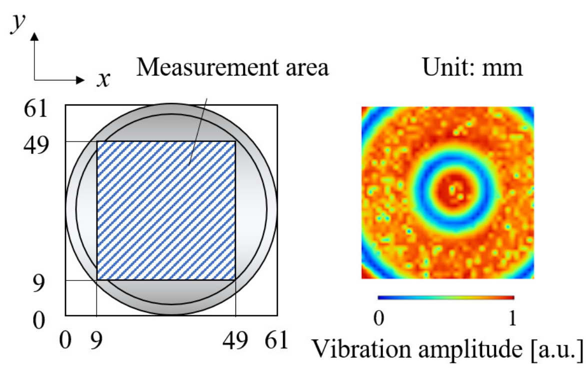

Fig. 2 Vibration amplitude distribution of the hemispherical vibration plate at 27.5 kHz.

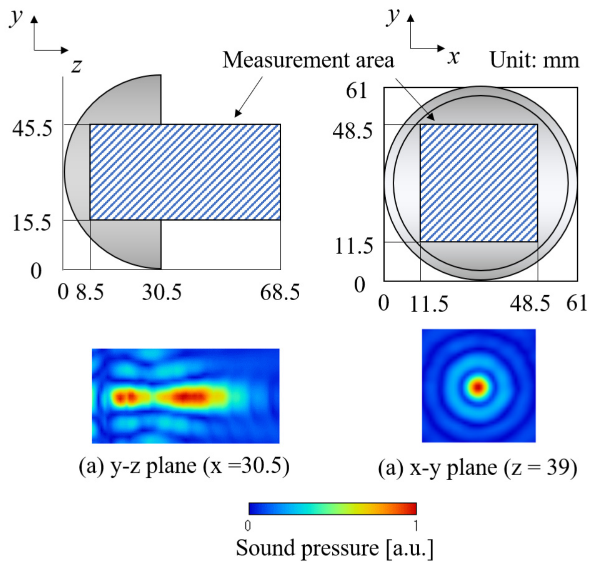

Fig. 3 Sound pressure distributions at 27.5 kHz in (a) *y*-*z* plane at x = 30.5 mm and (b) *x*-*y* plane at z = 39 mm.

3. Deformation of phantom

The thickness and the elastic modulus of epidermis on fingertips are approximately 1 mm and 136 kPa, respectively [2]. In this paper, two kinds of silicone gels (TSE3450 and TSE3062, Momentive Performance Materials) were employed and mixed to prepare a tissue phantom. The viscoelasticity of the phantom depended on the mixture ratio of two gels; TSE3450 and TSE3062. They were mixed at the weight ratio of 1 to 2. After adding a curing agent and degassing of the mixture, a phantom film (15×30×1.5 mm^3) was formed. The elastic modulus of the phantom was measured to be 110 kPa.

The tissue phantom film was placed perpendicularly to the sound axis at z = 39 mm. **Fig. 4** shows the surface deformation of the phantom and the sound pressure distribution on the surface. The surface deformation in the case with the input voltage amplitude of 40 V_{pp} was scanned at y = 23 to 38 mm using a laser displacement meter (LT-9000, Keyence). The plots and error bars indicate the average values and the standard deviations for five measurements. Comparing with the acoustic field without the phantom (Fig. 3), an acoustic standing wave was generated between the vibrating plate and the phantom and the sound pressure amplitude was increased; the maximum sound pressure amplitude on the phantom surface was 4.0 kPa. The tissue phantom was deformed by acoustic radiation force generated by the focused ultrasound, and the maximum displacement on the phantom was 115 μm. The surface profile correlated with the sound pressure distribution.

Acoustic radiation pressure acting at a boundary between two media is generated by the difference of acoustic energy densities. If the incident acoustic wave is assumed to be reflected perfectly at the boundary, the acoustic radiation pressure P can be expressed as $P = 2p^2 / \rho c^2$ where c is the speed of sound, p is the sound pressure, and ρ is the density of medium. From this equation, the acoustic radiation pressure at y = 30.5 mm can be estimated roughly to be 115 Pa (in this case, c and ρ are those of air).

4. Conclusions

The surface deformation of a tissue phantom by acoustic radiation force was measured. The focused ultrasound was irradiated from the semispherical vibrating plate, and the relationship between the acoustic field and the surface profile was investigated. The results showed that the surface deformation on the tissue phantom correlated with the sound pressure distribution. The acoustic radiation pressure on the surface of the phantom was estimated to be 115 Pa, and the maximum deformational displacement was 115 μm. We intend to investigate the deformation on fingertips in future research.

References

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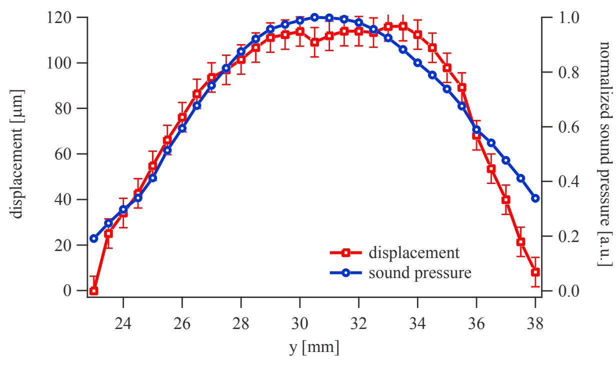

Fig. 4 Surface profile of the tissue phantom deformed by acoustic radiation force and the sound pressure amplitude distribution on the surface

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