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Ultrasonic Fields Designed for Effective Actuation of Soft Tissue Using Line Focus Array Transducers
超音波を用いた生体軟組織加振時の音場のアレイ型線状集束トランスジューサによる改良

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1. Introduction

Acupuncture has been developed based on the authority on experience. It is important to evaluate the effect of therapy quantitatively to elucidate the mechanism of acupuncture therapy. The measurement of the change in elastic properties of muscle due to the treatments is one of the strategies for quantitative evaluation of acupuncture therapy.

Recently, some remote actuation methods based on acoustic radiation forces have been reported. Nightingale et al. proposed an alternative imaging method in which focused ultrasound is employed to apply the radiation force to soft tissue for short durations[1)]. According to safety guidelines for the use of ultrasound, the recommended intensity is below 1 W/cm^2 for continuous waves. This value corresponds to an acoustic radiation force of 6.67 Pa, which is very small. Therefore, to generate measurable strain by acoustic actuation, the method to effectively apply acoustic radiation forces needs to be devised. In the present study, we improved ultrasonic fields to increase the efficiency of actuation using line-focus ultrasonic array transducer[2)].

2. Principle

2.1 Actuation method using acoustic radiation force

An experimental setup is illustrated in Fig. 1. When the elastic modulus of an object is greater than that of the surrounding media, one acoustic radiation force may generate only a change in the position of the object[2)]. In the study, for effective generation of strain in the object, two acoustic radiation forces respectively induced by two ultrasounds at frequencies f and f+Δf were applied to two different positions in the object from two different directions in synchronization as shown in Fig. 1. Therefore, the region pinched by two acoustic radiation forces was compressed along the horizontal axis.

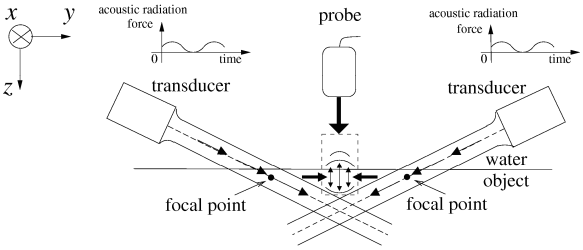

Fig. 1: Illustration of measurement.

With respect to the low-frequency component, the acoustic radiation pressure $P_R(t)$ is defined as the acoustic radiation force per unit area as follows: where p_0, R, ρ_1 and c_1 are the sound pressure of the transmitted ultrasound, the pressure reflection coefficient on the surface of an object, density and sound speed in the medium, respectively.

$$P_R(t) = \left(1 + R^2\right) \frac{p_0^2}{\rho_1 c_1^2} \left[1 + \cos\left(2\pi \Delta f t\right)\right], \qquad (1)$$

The displacement in the depth direction was measured by the ultrasonic *phased tracking method* [3)]. Additionally, strains between two different positions along an ultrasonic beam are obtained from the difference between displacements at these two positions.

2.2 Effective actuation by line focus transducers

Direction of the strains generated by point focused transducers and line focused transducers are illustrated in Figs. 2(a) and 2(b), respectively. When a region is compressed in y direction by two synchronized radiation forces generated by point focused ultrasonic field (Fig. 2(b)), the region expands in x and z directions due to its incompressibility. The expansion is diverged in x and z directions to keep the volume of the region to be constant. In this study, radiation forces were applied by two line-focus ultrasonic transducers, as shown in Fig. 2(b), by which the region can expand larger in the vertical (z) direction to preserve its

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volume compared with the case before two point-sources are applied.

Strains in the vertical (z) direction caused by point-focus and line-focus transducers are respectively expressed as follows:

$$\varepsilon_{pz} = \frac{\sigma_y}{E} \nu, \qquad (2)$$

$$\varepsilon_{lz} = \frac{\sigma_y}{E} \nu \cdot (1+\nu), \qquad (3)$$

where σ_y, E and ν are stress in the y direction, Young's modulus and Poisson ratio of an object, respectively. When the object is an incompressible material ($\nu = 0.5$) such as biomedical tissues, the strain generated by line-focus transducers is $1 + \nu = 1.5$ times larger than that generated by point-focus transducers. In this study, displacements $\{d_z(x,z)\}$ in the vertical (z) direction were measured as distributions on xz-plane.

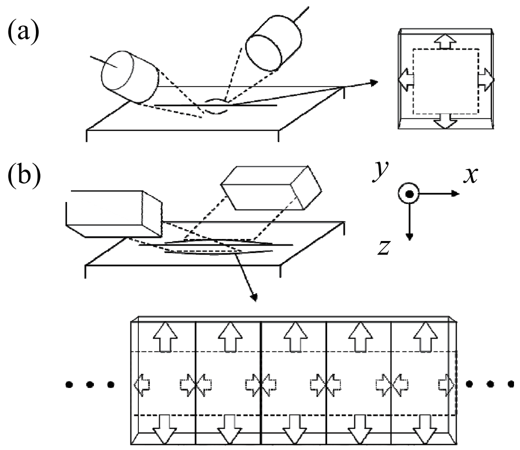

Fig. 2. Illustrations of strains generated by (a)point focus transducers and (b) line focus transducers.

3. Results

Figures 3(a) and 3(b) show the spatial distributions of displacements $\{d_z(x,z)\}$ in one cycle of acoustic radiation forces generated by the point focus transducers and the line focus transducers, respectively. Each ultrasonic transducer was driven by the sum of two continuous waves at two slightly different frequencies of 1 MHz and 1 M + 5 Hz. The ultrasonic beam was applied to the interface between oil and water. Using point focus transducer, generated displacement $\{d_z(x,z)\}$ was large only at the transducers' focal point. On the other hand, using line focus transducers, acoustic radiation forces are desired to be applied uniformly in the horizontal (x) direction so that the displacement distributes uniformly in a broad region. However, in Fig. 3(b), there were three regions where the amplitudes of displacements $\{d_z(x,z)\}$ were dominant (↓). The region for this was considered that a finite size of the transducer was vibrated uniformly because the transducer was composed of an element.

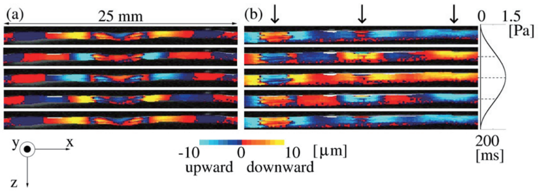

Fig. 3. The spatial distributions of displacements generated by (a) point focus transducers and (b) line focus transducers.

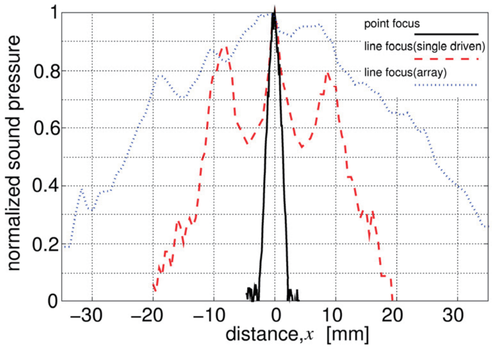

Fig. 4. The spatial distributions of sound pressure along x-axis at focal point measured for point and line focus transducers (single-element and array).

Figure 4 shows spatial distributions of sound pressure in the x-direction produced by point-focus and line-focus transducers. As shown in Fig. 4, there were three peaks in the sound pressure distribution produced by the single-element line-focus transducer. To overcome this problem, we constructed two line-focus array transducers composed of 34 elements (size of their apertures in the x-direction were twice as wide as those of single-element transducers). The arrays were separated three groups, 9 elements in both edges and central 16 elements. The voltages applied to the groups at both edges were 85% compared to those to the central 16 elements. As a result, a wider and smoother spatial distribution of sound pressure was successfully realized, as shown in Fig. 4.

4. Conclusions

In this study, line-focus array transducers were newly developed for more effective acoustic actuation.

References

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