NON-CONTACT ACOUSTIC MANIPULATION USING CROSSING ULTRASOUND

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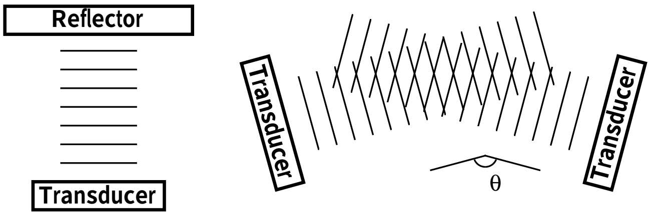
Abstract

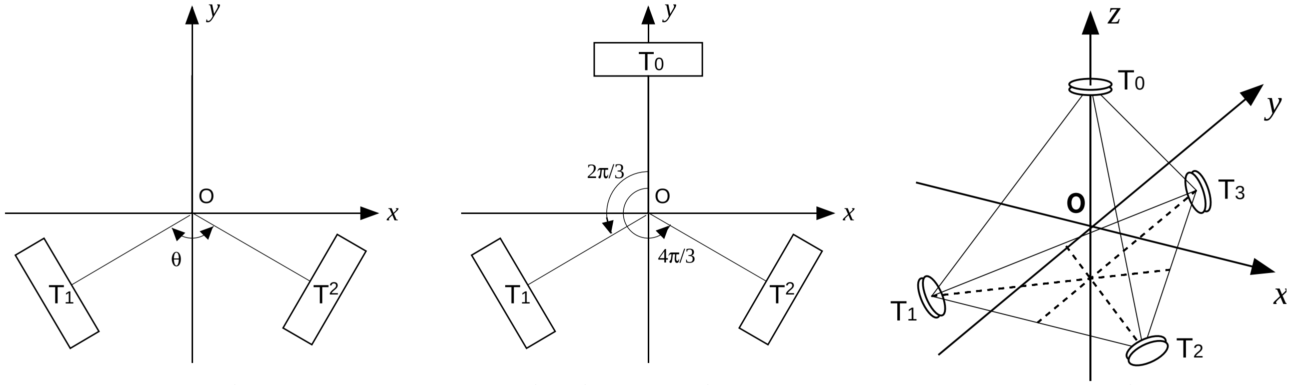
Non-contact micromanipulation technique is needed to develop micromachine technology. Using a standing wave field generated between a transducer and a reflector, it was possible to trap particles in water at nodes of the sound pressure distribution and transport them. The present paper describes an advanced technique to manipulate particles three-dimensionally using four transducers. The transducers were settled at each corner of a regular triangular pyramid with their sound-beam axes crossing at the center of the pyramid. When all transducers are driven in the same frequency, a standing wave field, which is distributed in three-dimensionally is generated in the crossing region. It is possible to move a particle in any direction in the three-dimensional space by shifting the phase of each transducer. Thus, three-dimensional non-contact manipulation of a particle has been accomplished.



(a) Conventional method (b) Crossing sound beams
Fig. 1. Generation of standing wave fields.

Introduction

When ultrasound traveling in a fluid is interrupted by an object, force to push the object is generated in the direction of the sound propagation[1]. This is called acoustic radiation pressure and the force due to it acts on an object without contact. Non-contact manipulation technique in a micro region can be realized by using acoustic radiation pressure[2-4], and the author has been studying various related phenomena. The papers in [5] described an ultrasonic micromanipulation method using a standing wave field generated between a transducer and a reflector. Although it was possible to trap particles in water at nodes of a standing wave field generated between them (Fig. 1(a)) and to transport them using a frequency-shifting operation, there were several problems such as unstable force due to resonance of the sound field and different movement among trapped particles. The paper in [6] proposed a method to generate a standing wave field using two or three sound sources without a reflector (Fig. 1(b)). There is no resonance in the sound field with this scheme, because each traveling wave does not return to the source. The present paper describes an advanced manipulation technique to realize three-dimensional transportation of particles using a standing wave field generated by four transducers, whose sound beam axes were crossing at a point in a three-dimensional space.



(a) Two transducers (b) Three transducers (c) Four transducers

FIG.2. Coordinate system of the sound field generated by two, three and four transducers.

Sound Field

Standing Wave Fields Generated by Plural Sound Sources

When two sound beams crossed at an angle of θ=180 degrees, each sound beam is reflected at the other transducer and it causes a problem of resonance of the sound field. Then, the two sound beams should be crossed at an angle θ less than 180 degrees (Figure 2(a)). The generated standing wave field is one dimensional.

It is possible to extend this scheme into two or three-dimensional cases by adding more transducers. Figure 2(b) shows the method to generate two-dimensional standing wave field using three transducers, whose sound beam axes were arranged with an angle of 120 degrees to each other in the same plane. Figure 2(c) shows an extension to the three-dimensional field. Four transducers were settled at each corner of a regular triangular pyramid with their sound-beam axes crossing at the origin of the coordinate. The sound beam axis of transducer T_0 is aligned to the *z*-axis, and the sound beam axis of T_3 is on the *yz*-plane. The transducers positions are given as

$$T_0(0,0,l), \qquad T_1\left(-\sqrt{\frac{2}{3}}l,-\frac{\sqrt{2}}{3}l,-\frac{1}{3}l\right),$$
$$T_2\left(\sqrt{\frac{2}{3}}l,-\frac{\sqrt{2}}{3}l,-\frac{1}{3}l\right), \quad T_3\left(0,\frac{2\sqrt{2}}{3}l,-\frac{1}{3}l\right) \tag{1}$$

where l is the distance from the origin to each transducer.

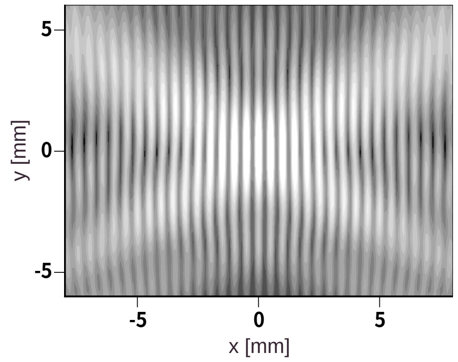
Calculated Sound Pressure Distributions

The sound field generated by crossing sound beams can be obtained by using a theoretical analysis. The sound pressure produced by a piston source in an infinite rigid wall can be expressed by the following Rayleigh's formula [7]:

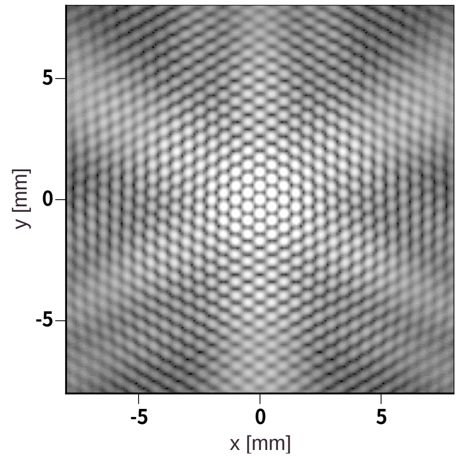
$$p = \mathrm{j}\frac{\rho c V_0}{\lambda}\exp(\mathrm{j}\omega t)\iint_F \frac{\exp(-\mathrm{j}kr)}{r}\,\mathrm{d}F\,, \tag{2}$$

where V_0 is vibrating velocity at the sound source, r is density of the medium, c is sound speed, λ is wavelength, ω is angular frequency, k is ω/c, and ρ is the distance between an arbitrary point on the transducer and the observation point. Of these, $\mathrm{j}\rho cV_0\exp(\mathrm{j}\omega t)/\lambda$ is the term depending on time t and calculations were done for $\iint F\{\exp(-\mathrm{j}kr)/r\}\mathrm{d}F$.

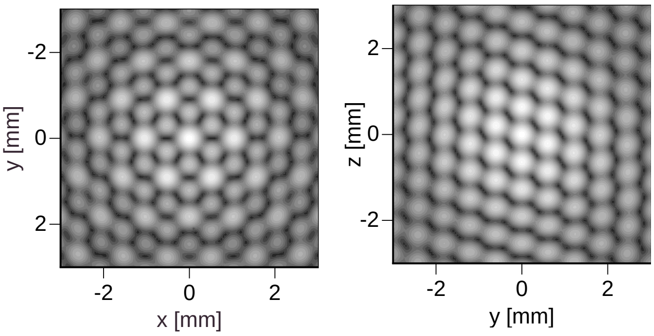
Figure 3 shows calculated sound pressure distributions. Every case was calculated near the crossing point of sound beam axes, when l=33 mm and λ=0.86 mm in water, which correspond to the experimental conditions in the next section. Figure 3(a) is the case of two transducers which are settled at the bottom of the right and left in this figure, respectively, and each sound beam travels toward the center. It forms a simple standing wave field, because the nodes and antinodes of the sound pressure are seen as dark and bright lines, respectively. The case with the third sound beam added at the top is shown in Fig. 3(b). A hexagonal pattern of the standing wave field is observed. Figures (a) and (b) are both the *xy*-plane including two or three sound beams. But, (c) and (d) are *xy*-plane and *yz*-plane generated by four sound sources. Both T_0 and T_3 are on the *yz*-plane in Fig. 4(d), and the interval between the nodes of sound pressure is (3/4)λ along each sound beam axis. When the phase of transducer T_0 or T_3 changes by 360 degrees, the pressure distribution of the sound field shifts by (3/4)λ along the sound beam axis.



(a) Two sound sources



(b) Three sound sources



(c) Four sound sources (*xy*-plane)　(d) Four sound sources (*yz*-plane)

FIG.3. Calculated sound pressure distributions.

Experiment

Experimental Setup

Figure 4 shows the experimental apparatus using four transducers. The transducers were flat disks 20 mm in diameter with a resonant frequency of 1.75 MHz. The disk element was mounted into a silicon rubber surrounded by an acrylic pipe of 30 mm in diameter. Four transducers were settled at each corner of the regular triangular pyramid, whose sound-beam axes were crossed at the center of the pyramid. The distance from the transducer to the crossing position of the sound-beam axes was 33 mm, which is the distance from the transducer to the last maximum in the axial sound pressure distribution. Electric signals generated by three synchronized function generators (NF, 1964) were amplified with three power amplifiers (ENI, 325LA, 50 dB) and applied to each transducer. The transducers were driven with a continuous sinusoidal wave of 1.75 MHz at an applied voltage of 15 Vpp. When polystyrene particles, whose specific gravity was 1.05 and with diameters from 100 to 500 µm, were poured with a pipette into the sound field, the particles were trapped at the nodes in the central region of the standing wave field.

Manipulation of Particles

Experiments for manipulation of polystyrene particles were performed by changing the phase of the transducer. When the phase of one of the four transducers was shifted, the trapped particle was transported along the sound beam axis of the transducer following the movement of the node in the standing wave field. The three-dimensional movement of a particle was captured with two CCD cameras. Camera 1 was settled on the *y*-axis, and camera 2 was settled on the *x*-axis. The two captured images were mixed using a central wiping unit and were recorded with a VCR.

Figure 5 shows an example of a multi-exposure photograph of the three-dimensional transportation of trapped particles. The right image shows the *xz*-plane captured by the camera 1, and the left shows the *yz*-plane captured by the camera 2. First, four transducers were driven at the resonant frequency of 1.75 MHz to generate a standing wave field and two polystyrene particles were trapped at the bottom. When the frequency of transducer T_0 changed to 1.749998 MHz, a constant negative shift of the phase of T_0 at 720 degrees/sec was realized and the trapped particles moved upward. After that, the frequency of T_0 was returned to 1.75 MHz. The frequency of T_1 changed to 1.749998 MHz just for a short time, after that it changed to 1.750002 MHz. Then, the particles moved along the sound beam axis of T_1.

Discussion

Moving Vector

Table 1 shows the moving distance of particles measured by image processing when the phase of each sound source changed for 360 degrees. The distance between the nodes of the sound field can be obtained using a theoretical analysis. When the angle θ (Fig. 1(b)) of the crossing sound beams varies in a plane defined by the two sound sources, the standing wave field changes its form. The distance between the nodes in the standing wave field is given by $\lambda/(2\sin(\theta/2))$ along the parallel line of these transducers (Fig. 6(a)). This relation holds in each pair of transducers T_0-T_1, T_0-T_2 and T_0-T_3 in this experiment using four sound sources. These distribution patterns of sound pressure are combined on the sound beam axis of T_0 (Fig. 6(b)). Then, the distance between the nodes is $\lambda/(2\sin^2(\theta/2))$ on the axis. As an example of this experimental case, if $\sin(\theta/2)=(2/3)^{1/2}$ (θ=109 degrees) the distance between the nodes is $(3/4)\lambda$, which is the same as the calculated sound pressure distribution on the axes T_0 and T_3 shown in Fig. 3(b). Table 2 shows a calculated distance of transportation

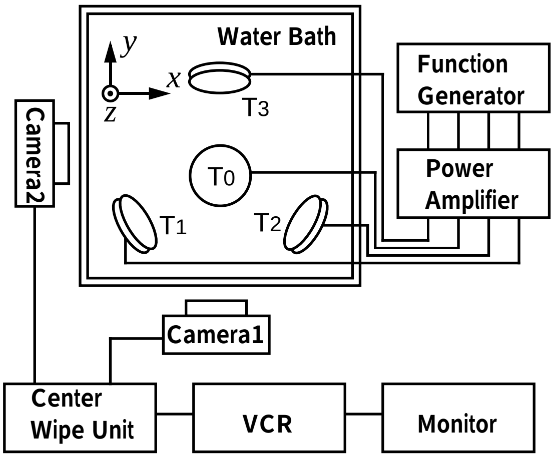


FIG.4 Experimental apparatus.

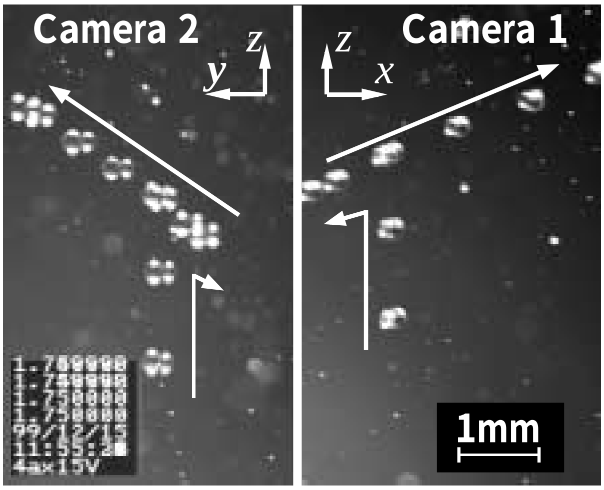


FIG.5 Three-dimensional manipulation of particles.
(Multi-exposure photograph)

Table 1. Measured distance of transportation.

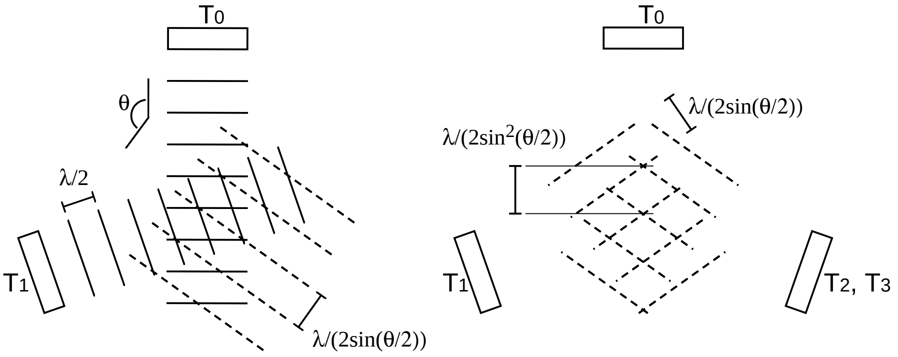
[mm]

Source	*x*-axis	*y*-axis	*z*-axis
T_0	0	0	-0.58
T_1	0.52	0.31	0.22
T_2	-0.51	0.29	0.15
T_3	0	-0.59	0.18

Table 2. Calculated distance of transportation.

[mm]

Source	*x*-axis	*y*-axis	*z*-axis
T_0	0	0	-0.64
T_1	0.52	0.30	0.21
T_2	-0.52	0.30	0.21
T_3	0	-0.60	0.21



(a) Two sound sources (b) Four sound sources

FIG.6 Superposition of the nodes of the sound pressure.

when the phase of each sound source changes for 360 degrees. It is confirmed that the vectors are the same as experimental ones. By comparing Table 1 and Table 2, the calculated results are nearly equal to the measured distances.

Conclusion

Trapping of particles and control of their positions were studied in water using acoustic radiation pressure in ultrasonic standing wave fields generated by crossing plural sound sources without reflectors. It was possible to generate a standing wave field one-, two- and three-dimensionally by two, three and four transducers. A three-dimensional standing wave field was generated by setting four transducers at each corner of the regular triangular pyramid with their sound-beam axes crossing at the center of the pyramid. Polystyrene particles were trapped at the sound-pressure nodes of the generated standing wave field. Since the node of the sound field moves as the phase of the signal to drive the transducer is shifted, it is possible to transport the trapped particles by changing the mutual phase among transducers. By assigning slightly different frequency to each transducer, transportation at constant speed was realized. It was possible to realize transportation along a curve by changing phases of two sound sources sinusoidally. A three-dimensional standing wave field was generated by setting four transducers at each corner of the regular triangular pyramid with their sound-beam axes crossing at the center of the pyramid. The three-dimensional movement of the particle was captured by two CCD cameras and was analyzed using the image processor. The result shows that the particle movement in experiment agreed with that expected from the theory. Thus, three-dimensional non-contact manipulation of a particle was accomplished.

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