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Design of an Acoustic Levitator for Three-Dimensional Manipulation of Numerous Particles *

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We present a design of an acoustic levitator consisting of three pairs of opposite transducer arrays. Three orthogonal standing waves create a large number of acoustic traps at which the particles are levitated in mid-air. By changing the phase difference of transducer arrays, three-dimensional manipulation of particles is successfully realized. Moreover, the relationship between the translation of particles and the phase difference is experimentally investigated, and the result is in agreement with the theoretical calculation. This design can expand the application of acoustic levitation in many fields, such as biomedicine, ultrasonic motor and new materials processing.

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The acoustic manipulation, as one of the noncontact manipulation techniques, has a huge potential in many fields, such as biotechnology,[1–3] analytical chemistry[4,5] and processing of materials.[6,7] Until now, several manipulation techniques have been explored, which can be used to levitate and manipulate particles in an acoustic field.

A single-axis levitator consisting of a transducer and a reflector (or two transducers) is widely used to levitate small objects on one axis.[8–11] Some single-axis levitator can even suspend high density materials such as iridium and mercury.[12,13] To achieve manipulation of the objects, researchers changed the positions of traps by moving the transducer or reflector,[14,15] switching the frequency,[16] and adjusting the phase differences of transducers.[17] Later, a two-dimensional ultrasonic manipulation of small objects was realized by different systems using phase controlling.[18–20] It should be noted, however, that the methods mentioned here can only levitate and move objects on an axis or a surface, which may limit further applications of acoustic manipulation.

Three-dimensional manipulation has attracted much attention in recent years. Some researchers simulated the three-dimensional acoustic field under different conditions,[21,22] and many devices were designed at the same time. Ochiai *et al.* set up a series of devices that consist of two or four modules of transducer array.[23–25] Hundreds of transducers in each module were controlled separately with adequate phase differences, generating multiple focal points. The small particles were levitated only in these points in a single plane, despite three-dimensional manipulation was carried out in this experiment. Omirou *et al.* designed a modular levitation system with two phased arrays.[26] The 3D movement of particles was achieved by controlling amplitudes and phases of the transducers. Although several modules were joined to scale the levitation space, the number of suspended particles was still relatively small. Moreover, a latest work carried out by Marzo *et al.* proved that even a single-sided array has the ability to translate and rotate particles.[27] The study optimized the phases of transducers to create optimal traps at the desired positions. However, the number of traps decreased because the acoustic wave was focused, thus only a few particles could be levitated.

In this work, we first calculate the distribution of traps in an acoustic field superposed by three orthogonal standing waves. It is found that a large number of acoustic traps can be produced, at which particles are able to levitate. Then, based on this analysis, we design a device including three pairs of opposite ultrasonic transducer arrays to create this acoustic field. Moreover, the reflections will disrupt the capabilities of manipulation, thus we design a grid structure for the transducer arrays. To test the practicability of the device, the phase of wave emitted by one transducer array and the distribution of traps are simulated. The relationship between the moving distance of a particle and the phase change is experimentally investigated by actual measurement, and the result obtained is consistent with the theoretical prediction. The approach that we present here is a technique proposal that allows the control of numerous particles simultaneously in three-dimensional space. This technique is applicable to the case when numerous small objects such as cells and living materials need to be observed and compared.

The acoustic radiation force $\boldsymbol{F}$ exerting on a small particle can be decided by the gradient of the Gor'kov

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potential $U_{\rm rad}$,[28]

$$\boldsymbol{F} = -\nabla U_{\rm rad}, \tag{1}$$

where $U_{\rm rad}$ can be expressed as

$$U_{\rm rad} = V_{\rm p}\Big[\frac{1}{2\rho c^2}\langle p^2\rangle - \frac{3}{4}\rho\langle v^2\rangle\Big], \tag{2}$$

in which ρ is the density of the medium, c is the sound velocity, $V_{\rm p}$ is the volume of the particle, p is the sound pressure, v is the velocity of particle of the medium, p and v can be decided by a specific acoustic field. The particles will be trapped at the place where $U_{\rm rad}$ has local minima, called acoustic traps.

To achieve three-dimensional manipulation of the particles, we consider using three orthogonal standing waves superposed by three pairs of opposite plane waves. For each pair of plane waves, the phase of one plane wave is adjustable, while the other is constant. Therefore, three orthogonal standing waves are expressed as

$$\begin{aligned} p_x &= 2p_0\cos\Big(\omega t + \frac{\phi_x}{2}\Big)\cos\Big(kx - \frac{\phi_x}{2}\Big),\\ p_y &= 2p_0\cos\Big(\omega t + \frac{\phi_y}{2}\Big)\cos\Big(ky - \frac{\phi_y}{2}\Big),\\ p_z &= 2p_0\cos\Big(\omega t + \frac{\phi_z}{2}\Big)\cos\Big(kz - \frac{\phi_z}{2}\Big), \end{aligned}$$

where ϕ_x, ϕ_y and ϕ_z are the phase differences between two opposite plane waves, respectively. The superposition value of sound pressure for three orthogonal standing waves is

$$p(x,y,z) = p_x + p_y + p_z.$$

Knowing $p(x,y,z)$, we can calculate the velocity v, thus $U_{\rm rad}$ can be solved.

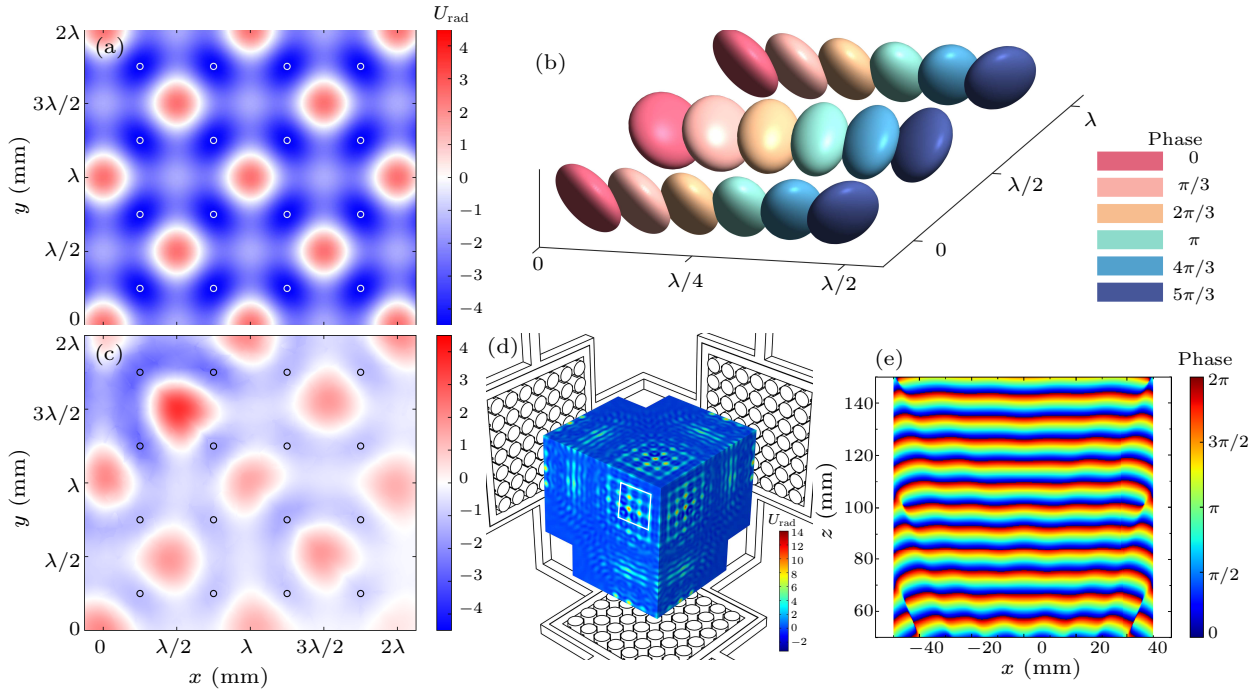

Fig. 1. (a) Schematic of the distribution of acoustic traps on the x–y plane. The white circles mark the trapping positions. (b) Schematic of the movement of acoustic traps. The curves are isosurfaces of $U_{\rm rad}$ wrapping the traps. This schematic shows how three traps move under different phases. (c) Simulation result of $U_{\rm rad}$ created by the device on the cross section parallel to the x–y plane and pass through traps. The black circles represent the acoustic traps calculated by theory. (d) Simulation result of $U_{\rm rad}$ created by the device. The cross section for (c) is marked by white square. (e) Phase of the wave emitted by one transducer array on the x–z plane. The array is placed on the x–y plane and faces to the positive direction of the z axis.

The distribution of acoustic traps on the x–y plane is shown in Fig. 1(a). Because the acoustic field is symmetric, the traps on y–z and x–z planes have the same distribution. The distance between two adjacent acoustic traps is $\lambda/2$. As ϕ_x, ϕ_y or ϕ_z changes, the acoustic traps move along x, y or z direction. Figure 1(b) is the schematic of the movement of acoustic traps when phase changes. If ϕ_x, ϕ_y or ϕ_z shifts from 0 to $2k\pi$, the moving distance of the particle is $k\lambda/2$.

The conclusion obtained above provides the basis for our design. The device that we designed consists of three pairs of opposite transducer arrays that create three orthogonal standing wave capable of suspending objects in mid-air, as shown in Fig. 2. Three pairs of opposite transducer arrays are fixed along x, y and z directions, respectively. The distance between two opposite arrays is 20 cm.

Each transducer array has 7×7 transducers fixed

on a grid structure backboard. The center distance of two adjacent transducers is 12 mm. The used transducer (HY-1040ABS-T) is 10 mm in diameter and 7 mm in height. Different from the phased array focusing,[29–32] the transducers on each array are connected in parallel so that the phase of sound wave emitted by every transducer is identical, i.e. the wave emitted by an array is an approximate plane wave.

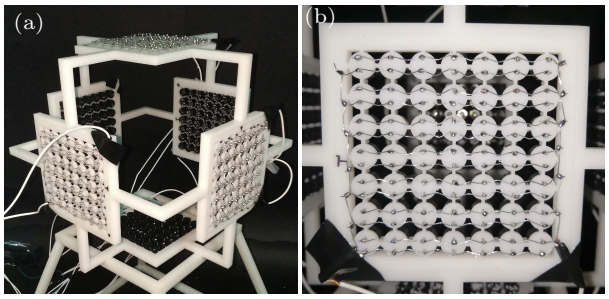

Fig. 2. (a) Photo of the device. (b) Photo of the transducer array.

It should be noted that the reflection of backboard to sound wave can disturb and weaken the sound pressure so that the stability of manipulation is significantly affected.[33] Therefore, we design the grid structure of the backboard to allow the sound wave to pass through and to greatly reduce the reflection. In addition, the device is fixed on a bracket to avoid the reflection from the table.

Three Arduino Nanos signal generators are used. Each Arduino Nano generates two signals, which have an adjustable phase difference to control two opposite arrays separately.

The key point in the design is that three Arduino Nanos should share the same clock signal to synchronize the output signals and to avoid the influence of slight frequency differences among oscillators. The signals generated by Arduino Nanos are 40 kHz and 5 V_{p-p} square wave. This signal is sent to an L298N Dual H-Bridge motor driver to amplify. The output of the driver is then sent to the transducer arrays.

To test the practicability of our design, the distribution of traps is simulated based on the parameters of the levitator. The simulation result of the levitation space in mid-air is displayed in Fig. 1(d). For clarity, the cross section, which is parallel to the x–y plane and passes through traps, is depicted in Fig. 1(c).

The positions of the acoustic traps present a latticed structure similar to the theoretical calculation. Owing to the symmetry, the images of cross sections parallel to y–z and x–z planes are the same. The phase of sound wave emitted by one transducer array is also simulated. Figure 1(e) shows that the wavefront is almost a plane parallel with the array, which indicates that the wave generated by one transducer array is approximately a plane wave.

For the experiment, we first demonstrate the levitation effect of our device using expanded-polystyrene particles as shown in Fig. 3. To reduce the disturbance to the sound field, the particles are put into the device by a scoop made of gauze. It can be seen from Fig. 3(a) that a large number of particles are levitated in the air. Because the size of traps is larger than the particle size, as well as the electrostatic force between the particles is inevitable, some particles may gather together. Another photo taken in a different view is shown in Fig. 3(b), which indicates that the particles are distributed in an approximate latticed structure. Two cameras are used to locate the levitation positions of particles.[34] The distance of two adjacent particles measured is 4.33 mm in average, which is almost consistent with the theoretical value $\lambda/2 = 4.30$ mm (20℃, 58% relative humidity, 1 atm).

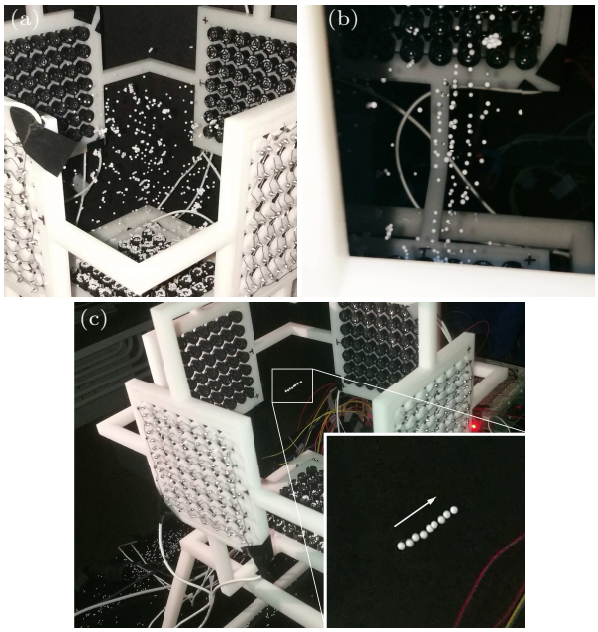

Fig. 3. Levitation effect of the device. (a) Numerous particles are levitated in mid-air. (b) The latticed structure of particle distribution. (c) Movement of a single particle as phase difference changes in a single experiment. This image is composed by multiple images taken in the experiment to clearly show how levitation position changes. The white arrow shows the moving direction of the particle.

Next, we manipulate the movement of particles by adjusting the phase difference between two opposite transducer arrays. As an example, Fig. 3(c) displays the actual position time series of a particle as phase difference changes. It is obvious that the particle moves along the corresponding direction as phase difference changes.

Furthermore, the quantitative relationship between particle movement along x, y and z directions and the phase difference is measured. The measurement result is shown by circles in Fig. 4. Meanwhile the result of theoretical calculation is depicted by the solid line in Fig. 4. The theoretical result is in good

agreement with the experimental data, which indicates that the experiment can achieve a controlled movement for a levitation particle, as is expected.

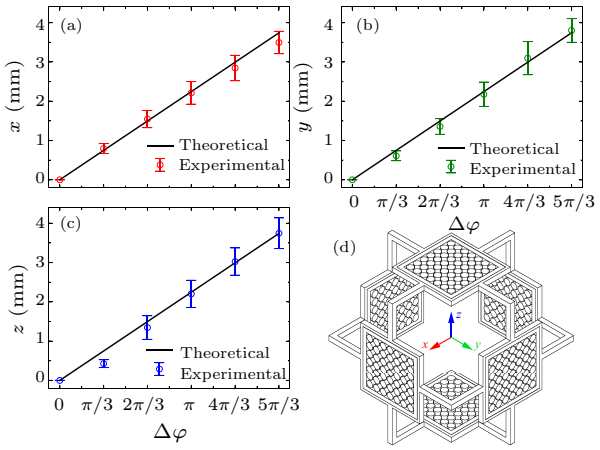

Fig. 4. Levitation position as phase difference changes in three different directions.

In conclusion, we have designed a levitator to levitate and manipulate numerous particles in mid-air, which is composed of three pairs of face-to-face transducer arrays. By changing the phase difference of transducer arrays, the movement of particles is controllable in three dimensions. It is worth mentioning that reducing the reflection of transducer arrays is important to maintain the stability of levitation and manipulation. Furthermore, the relation between the positions of particles and phase difference is experimentally investigated, which is in agreement with the theoretical calculation. Considering the application in future, the driving power of transducers should be increased to levitate much denser small objects. Our device provides a technical proposal to manipulate a large quantity of particles, which creates more possibilities of acoustic manipulation technology in many fields, such as biotechnology, drug selection, non-contact ultrasonic motor, and research of new materials.

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