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Acoustic levitation and manipulation by a high-frequency focused ring ultrasonic transducer

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Xiaoyang Chen,[1,a),b)] Kwok Ho Lam,[2,a)] Ruimin Chen,[3] Zeyu Chen,[3] Xuejun Qian,[3] Jun Zhang,[4] Ping Yu,[1] and Qifa Zhou[3,5,b)]

AFFILIATIONS

[1]College of Material Science and Engineering, Sichuan University, Chengdu 610064, People's Republic of China
[2]Department of Electrical Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[3]Department of Biomedical Engineering and NIH Transducer Resource Center, University of Southern California, Los Angeles, California 90089, USA
[4]College of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, People's Republic of China
[5]Department of Ophthalmology, University of Southern California, Los Angeles, California 90089, USA

[a)]**Contributions:** X. Chen and K.-H. Lam contributed equally to this work.
[b)]**Authors to whom correspondence should be addressed:** xiaoyang189@scu.edu.cn and qifazhou@usc.edu.

ABSTRACT

Recently, acoustic levitation for non-contact micro-particle manipulation has been attracting great interest in physical, biological, and medical applications. Among the state-of-the-art manipulation technologies, single beam acoustic tweezing exhibits advantages of providing stronger trapping force and deeper penetration depth in tissues, inducing less tissue damage, and a simple configuration involving only one device. However, particle trapping by the single beam acoustic tweezer could only be operated on a smooth two-dimensional substrate, which limits the potential for real applications. Here, we report an initial attempt to acoustically levitate an individual micro-particle stably in water and manipulate the levitated micro-particle arbitrarily two-dimensionally by simply employing a 60-MHz focused ring ultrasonic transducer. The proposed working mechanism agrees well with the phenomenon. This approach could not only acoustically levitate and manipulate a micro-particle on a culture dish and on a mylar film, but could also work properly in levitating and manipulating a micro-particle placed inside the polyimide tube. This simple and low-cost approach is extremely useful for effective non-contact micro-particle manipulation without having critical concerns on the substrate properties.

Acoustic waves are capable of exerting acoustic radiation forces to levitate particles with a wide range of sizes and materials through air and water.[1,2] Multiple levitation and manipulation methods using ultrasonic waves have been proposed to satisfy this need, including single beams,[3] standing waves,[1] and surface acoustic waves.[4] The most common acoustic levitators are single-axis levitators using acoustic standing waves.[5–7] Recently, acoustic streaming by the surface standing acoustic wave (SSAW)-based technique was also utilized to lift up micro-particles.[8] However, this technique often requires a pair of parallel or orthogonal transducers, which limits the feasibility of *in vivo* applications. Among these methods, a single-sided device or a single beam acoustic tweezer (SBAT) has advantages of providing stronger trapping force, offering deeper penetration depth in tissues and employing only one transducer, which show great potential for *in vivo* and clinical applications.[9–16]

However, acoustic levitation is relatively complicated for single-sided devices. There are two approaches to form acoustic levitation according to the same or opposite direction between the gravity and the ultrasonic wave propagation. First, when the targeted particle is placed above the ultrasound wave emitter, holographic acoustic elements have been proposed to manipulate, translate, and rotate the levitated particle in air.[3] Besides, the near-field acoustic levitation can also levitate heavy planar objects at a distance of tens of micrometers from the transducer radiating surface.[17,18] Second, when the targeted particle is placed underneath the ultrasound wave emitter, the trapped particle can only suffer from lateral forces, which has to stay on

a plane due to the acoustic radiation force induced by acoustic wave scattering.[16,19] To overcome this problem, a negative pulling force or a negative gradient force opposite to the propagation direction has been introduced to draw the particle back to the transducer such that the device has the capability of three-dimensional trapping, which has been validated from the experimental and theoretical analyses.[20–22] Array configuration and ultrasound beam-formation, like a vortex acoustic beam,[22,23] are usually required to meet the above approach. However, several factors such as high cost and bulky size of the array transducer, high complexity of beam-steering, and time-consuming fabrication process have limited those devices for rapid and extensive applications. For using a single element high-frequency ultrasonic transducer, it is always challenging to induce the acoustic levitation unless there is a reflector with high acoustic impedance that can offer strong enough reflected ultrasound waves to form a standing wave without considering the attenuation of the high frequency ultrasound waves.

In this study, an ultrasound wave emitter was designed without employing the reflector. Based on the single element transducer configuration, the device is capable of reducing the scattering force from incident ultrasound waves as well as strengthening the reflected wave from the bottom along the central axis of the beam. This would reduce the cost and the complexity. The capability of this ultrasonic emitter was demonstrated to levitate and manipulate a 10 μm micro-particle in water under the following three conditions: (i) micro-particles dispersed in a cell culture dish; (ii) micro-particles dispersed in a chamber with a mylar film as the substrate; and (iii) micro-particles located inside a polyimide tube.

When the ultrasound waves are in contact with the micro-particle, the momentum transfer of ultrasonic energy from the incident ultrasound wave results in ultrasonic radiation forces applied to the sphere.[24,25] The forces can be classified into two types: the scattering force pointing in the direction of ultrasound wave propagation and the gradient force pointing towards the center of the beam. The gradient force is the source of lateral forces to trap and manipulate particles in the lateral direction. The formation of gradient force is strongly related to the Gaussian beam which has a gradient distribution in the lateral direction.[26–28] For the single element transducer, it is difficult to produce a negative gradient pulling force along its axis. On the contrary, the particle would be easily pushed away by the scattering force.[19] Thus, a relatively simple and effective approach to reduce the scattering force along the beam axis has been suggested by using a ring configuration.[29] Nevertheless, the relatively weak scattering force from the incident wave would still push the particle away from the transducer. Since two opposite propagating acoustic beams would form a stationary wave to cancel the radiation force in the case of a single-axis levitator, this inspired the use of the reflected wave from the substrate to produce the second scattering force on the targeted particle. This second scattering force could be used to balance the first scattering force (induced by the reaction of ultra-sound waves and particles) and the particle gravity. In order to strengthen the reflected wave and lower the quality requirement of the substrate, the focus of the ring transducer would be adjusted on the substrate during levitation and manipulation.

The concept of levitating micro-particles using the single-element transducer is illustrated in Fig. 1(a). The focused ring transducer would emit the incident acoustic waves along its axis of wave propagation and mainly focus on the substrate (black dotted line). Although the waves are focused on the substrate, a small portion of ultrasound waves is still exerted on the targeted micro-particle such that the waves would be scattered. As shown in Fig. 1(a), Scattering force I pushes the particle towards the focus of the transducer. The reflected ultrasound wave from the substrate would be incident on the particle to produce Scattering force II, which is in the opposite direction of the propagating beam so as to balance the gravity and Scattering force I. To levitate and manipulate the particle, the mechanism is closely related to the intensity distribution of incident ultrasound waves, which was investigated through the simulation.

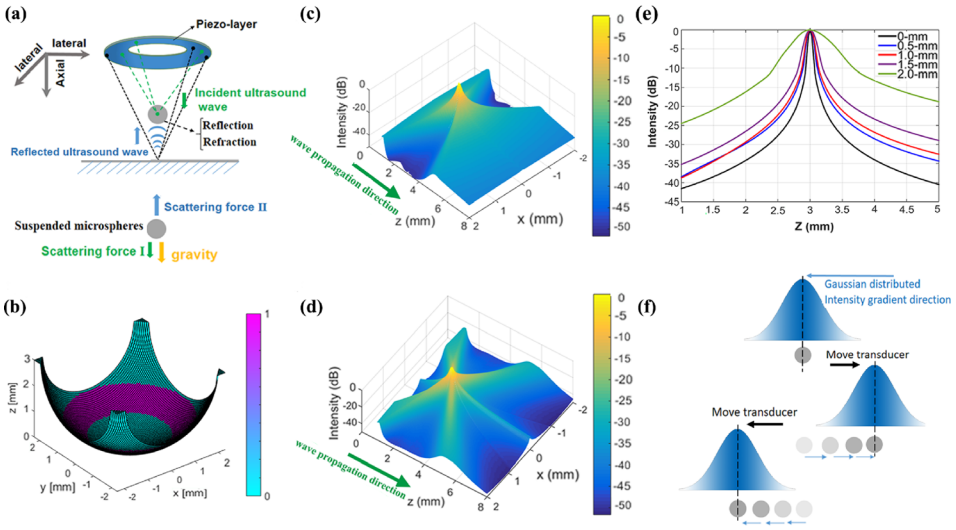

FIG. 1. (a) Simplified illustrations of levitating an individual 10-μm micro-particle by using a single-element high-frequency ultra-sonic transducer with a focused ring aperture. (b) The focused piezoelectric ring element meshed for ultrasound field simulation. (c) The simulated intensity distribution (x-z plane) of ultrasound waves emitted by the focused circular element. (d) The simulated intensity distribution (x-z plane) of ultrasound waves emitted by the focused ring element. (e) The effect of the inner diameter of the ring on the simulated ultrasonic intensity distribution along the central axis of the ring (x = 0 mm) with an outer diameter of 4 mm. (f) The force to move the micro-particle in the lateral direction from the Gaussian intensity distribution along the lateral direction of the focused ring transducer.

The focused piezoelectric ring element was meshed with many small elements for the simulation of the ultrasonic intensity distribution as shown in Fig. 1(b). The elements with color "1" in the color bar are the piezoelectric material that are the only active elements for contributing to the final intensity distribution of ultrasound waves in the simulation. To show the unique acoustic field characteristics of the ring aperture, the focused circular element with the same aperture size was also simulated. Figures 1(c) and 1(d) show the simulated results of intensity distribution (x-z plane) of ultrasound waves emitted by the focused circular and ring piezoelectric elements by using a Field II simulation program,[30] respectively. Compared with the focused circular element, the ring configuration contributes the relatively large gradient in the axial acoustic intensity from the center to the edge of the ring. In the focal region, the intensity is much stronger and highly focused for the ring configuration. This should be attributed to the existence of a hole in the middle of the ring element, which would not contribute ultrasound from its center and reduce the axial intensity of the incident wave from the element surface to the focal point. Meanwhile, the lateral intensity of the incident wave exhibits the Gaussian distribution. Figure 1(e) shows the effect of the inner diameter of a 4-mm diameter ring on the simulated ultrasonic intensity distribution along the central axis of the ring (x = 0 mm). It was clearly seen that the intensity distribution on the focal plane becomes asymmetric along the axial direction when the inner diameter of the transducer increases. This axial asymmetric intensity is the key factor for levitating the micro-particle. Besides the scattering force induced by reflections, the refraction between the medium and the particle would also offer the gradient force to move the particle laterally due to the Gaussian intensity profile.[19,24] Figure 1(f) depicts the movement of the particle with the transducer in which the particle is always pulled towards the beam focus in the lateral direction.

A lithium niobate single crystal was employed to fabricate the single-element focused ring ultrasonic transducer with the center frequency of 60 MHz. According to the simulation result of the maximum axial asymmetric intensity distribution (x = 0 mm), the outer diameter and the inner diameter of the transducer were chosen as 4.0 mm and 2.6 mm, respectively. In order to reduce the deviation and the distortion of the ultrasound beam affected by the inhomogeneous surface or polyimide tube, a tightly focused transducer with an f-number of 0.75 was developed by press-focusing technique.[31,32] The focal length of the ultrasound beam was about 3 mm, and the calculated ultrasound wavelength emitted by the focused ring transducer was about 25 μm. The experimental setup for trapping, levitating and manipulating the micro-particles by the single-element focused ring ultrasonic transducer is shown in Figs. 2(a) and 2(b). A cross-sectional view of the design and the photograph of this transducer is shown in Fig. 2(c). This high-frequency ultrasonic transducer was set in a chamber of distilled water, which was mounted on a three-axis motorized linear stage and controlled by a customized LabVIEW program. A CMOS camera combined with an inverted microscope (IX-71, Olympus, Japan) was used to record the motion of the trapped particle. Before the trapping experiment, a pulse-echo test was performed to make sure that the ultrasonic waves generated by the transducer were focused at the bottom of the

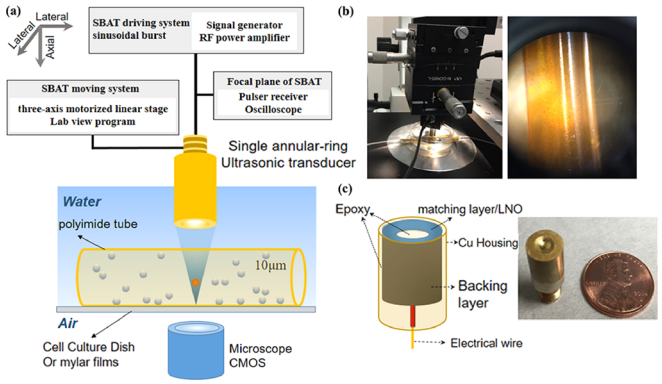

FIG. 2. The experimental setup for trapping, levitating and manipulating the micro-particles. (a) Schematic diagram of suspending and manipulating 10-μm diameter micro-particles in a polyimide tube (diameter: 1 mm) by using a single-element high-frequency focused ring ultrasonic transducer. (b) Photograph of the experimental setup with a polyimide tube filled with micro-particles. (c) Cross-sectional view of the design and the photograph of the final transducer prototype.

chamber or polyimide tube. The testing distance at which the intensity of the echo is the strongest was the focal length of the transducer. In our experiment, polystyrene micro-particles (Megabead, NIST traceable particle size standard, Polyscience, Inc., Warrington, PA) with the mean diameter of 10 μm were used. The sound speed and the density of the microparticles are about 2400 m/s and 1.05 g/cc, respectively. The acoustic impedances of a 0.9 mm-thick culture dish, a 0.025 mm-thick mylar film, and a 0.077 mm-thick polyimide tube are about 2.5 MRayl, 3 MRayl, and 3.6 MRayl, respectively. The fractions of the transmitted ultrasound are about −1.52 dB for mylar films, −6.15 dB for the polyimide tube, and −23.64 dB for the cell culture dish. The transducer was driven in a sinusoidal burst mode by a function generator (AFG3251, Tektronix, Anaheim, CA) and then amplified by a 50 dB power amplifier (525LA, ENI, Rochester, MN). To demonstrate the capability of single micro-particle manipulation, the transducer with the trapped particle was moved in a random manner by the motorized stages.

The results of acoustically levitating and manipulating a single 10 μm microparticle are illustrated in Fig. 3 (also see video 1 in the supplementary material). As the image appearance of objects under a microscope would be different based on their depth differences when the optical focal plane of the microscope was fixed, the acoustic levitation was demonstrated along this phenomenon. The first experiment was conducted with micro-particles in a culture dish (substrate). The optical focal plane of the microscope was initially focused on the bottom of the culture dish. As shown in Fig. 3(a), almost all micro-particles were deposited at the bottom (sharp image) except one that was acoustically levitated (blurred image). When the optical focal plane was raised towards the transducer, the blurred micro-particle becomes gradually clear. When the optical focal plane was focused on the micro-particle, it was clearly found that this micro-particle could be manipulated effectively by using an excitation frequency of 60 MHz as shown in Fig. 3(b). Figure 4 shows the optical image of a single levitated micro-particle

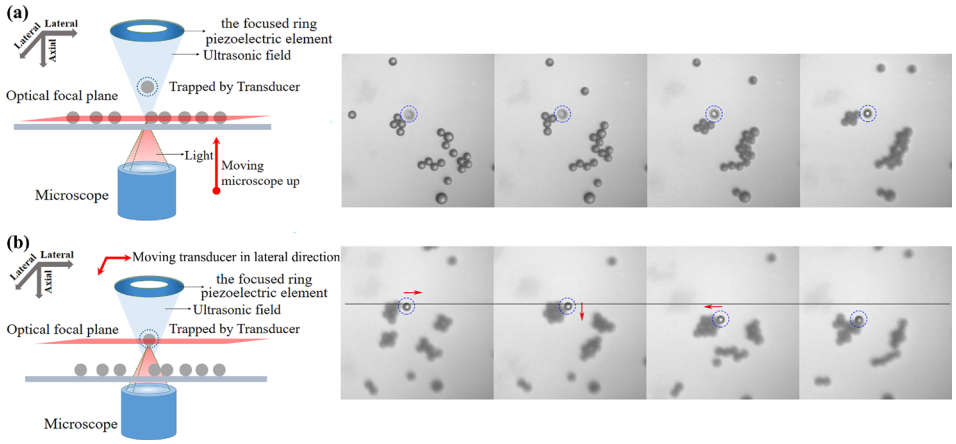

FIG. 3. Levitating and manipulating a single 10-μm micro-particle using a focused ring transducer. (a) The micro-particle that levitated from the bottom of the cell culture dish was initially seen blurred, and it got clearer on raising the focal plane of the microscope towards the transducer. (b) The levitated micro-particle was focused by the microscope. The red arrow is used to indicate the movement of the ring transducer. A blue circle is a trapped micro-particle, while a black line is given as a reference to show the location change of the micro-particle. The levitated micro-particle was manipulated along the random movement of the ring transducer. The manipulation of the trapped levitated particle was recorded by the CMOS camera.

when the focal plane of the microscope was focused on it. It should be noted that only one micro-particle was levitated among a number of micro-particles in the chamber. Besides, it can be seen that the levitated particle was located in the center of the circular spot that was formed by the light reflection of the concave surface of the transducer, which indicates that the particle was located in the central axis of the ring. The results agree well with the theoretical analysis, which prove that the focused ring transducer could levitate and effectively manipulate the individual micro-particle without having contact with the substrate.

Except for the culture dish, a mylar film with a different thickness and acoustic impedance was used to study the influence of the substrate. By focusing the ultrasound beam on the mylar films, the trapping and levitating processes can be clearly seen in Fig. 5(a) (also see video 2 in the supplementary material).

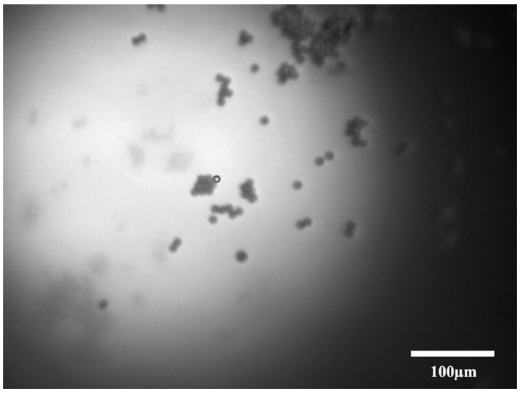

FIG. 4. The optical image of a single micro-particle acoustically levitated by a focused ring ultrasonic transducer when the focal plane of the microscope was focused on this levitated particle.

Initially, the particle was observed to move a very short distance along the lateral direction when the transducer and the microscope were kept at a fixed position, which is probably attributed to the gradient force produced by the transducer. Then, the micro-particle was levitated from the mylar film, as indicated by the clear images of the micro-particle, which was mostly driven by Scattering force II. The transducer was then moved randomly along the lateral direction to ensure that the particle was trapped. The demonstration shows that the particle can still be levitated and manipulated along the movement of the focused ring transducer even the substrate was with very weak acoustic reflection characteristics. Figure 5(b) shows that a single 10 μm micro-particle inside the polyimide tube could also be levitated and manipulated effectively by using the focused ring transducer located outside the tube (also see video 3 in the supplementary material). The result shows that the levitation and manipulation could also be performed even the target micro-particles are enclosed in the tube. This work provides a promising approach for intravascular drug delivery performed outside the blood vessels, in which the levitation effect could enhance the therapeutic delivery efficiency without considering the effect of the blood vessel wall.

This paper aims to offer a simple, low-cost but effective approach to levitate and manipulate an individual 10 μm micro-particle in water by using a 60-MHz single-element ultrasonic ring transducer with a focused aperture. The focused ring aperture was shown to be capable of levitating and manipulating the micro-particle on the substrates made of different acoustic impedance materials. This would be a very promising feature because the material and the quality of the substrate are no longer the critical concerns for performing the effective manipulation. Besides, it was also shown that the micro-particle inside the polyimide tube could be levitated and manipulated by the focused ring transducer located outside the tube. Since the trapped particle was acoustically levitated, this approach would

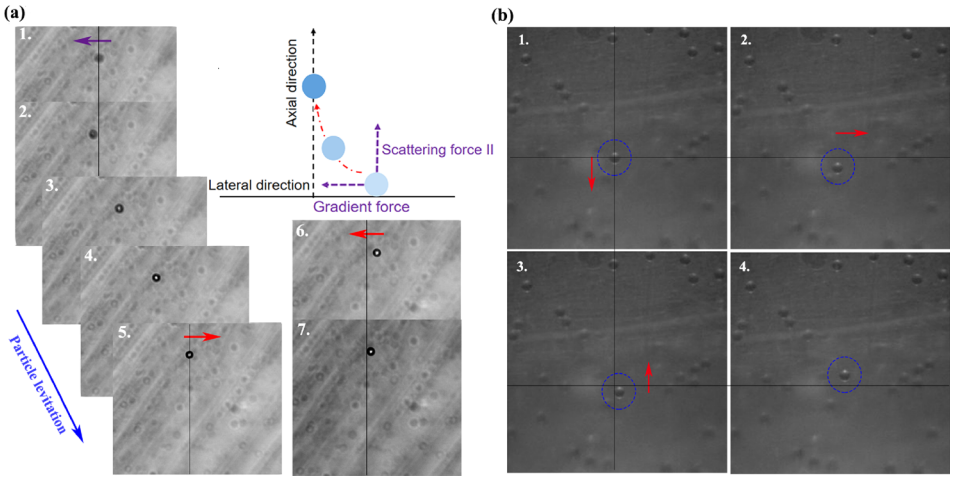

FIG. 5. Levitating and manipulating a single 10-μm micro-particle under different conditions using a focused ring transducer. (a) The micro-particles were placed on a mylar film. The purple arrow indicates the movement of the micro-particle, while the red arrow indicates the movement of the ring transducer; (b) the micro-particles were injected into the 1 mm-diameter polyimide tube. The red arrow indicates the movement of the ring transducer. The blue circle indicates the trapped micro-particle, while the black grid lines are given as a reference to show the location change of the micro-particle.

be very useful for developing efficient non-contact micro-particle manipulation and delivery. Moreover, this work also reveals that the structural design of the acoustic stack could be another effective approach to obtain different ultrasonic field distributions for specific applications.

See supplementary material for the videos (1)–(3) on acoustically levitating and manipulating a single 10 μm microparticle on a culture dish (video 1), on a mylar film (video 2), as well as in the polyimide tube (video 3) by a 60-MHz focused ring ultrasonic transducer.

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