Improvement of Acoustic Trapping Capability by Punching Specific Holes on Acoustic Tweezers

Haojie Yuan and Yanyan Liu(✉)

School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200072, China
yyliu2014@shu.edu.cn

Abstract. It is found that small particles can be successfully manipulated by the acoustic tweezers. This paper presents a method to improve the acoustic trapping capability by punching specific round holes on two vibrating V-shaped metal strips of the acoustic tweezers. A particle is trapped under the sharp edges of metal strips with some specific round holes. Its trapping capability is improved under certain conditions compared with the original acoustic tweezers. A finite element model is developed to calculate the acoustic radiation force. The effects of the radius, the number and the arrangement of the round holes on the acoustic radiation force on the top surface of the particle are discussed. It is found that the acoustic radiation force increases obviously when the radius of the hole is more than a certain magnitude by changing the vibrational mode of the acoustic tweezers. With the increase of number and the row in vertical direction of the round holes, the acoustic radiation force acting on the particle increases correspondingly.

Keywords: Acoustic radiation force · Acoustic manipulation · Acoustic tweezers · Finite element method

1 Introduction

The acoustic forces excited by kilohertz or megahertz frequency can reach a magnitude that is in the range of small particle's weight, so that these can be used to manipulate the particles. Acoustic manipulation technology has practical applications in bioengineering [1], nanofabrication [2], energy efficient systems and clean utilization of coal [3], with the advantages of less damage and selectivity to samples [4, 5] and simple device structures. The acoustic radiation force used to collect, separate and transport particles is generated from the spatial non-uniformity of the kinetic and potential energy density around manipulated samples. The different motivation models and device structures utilized to generate acoustic radiation forces have been proposed and investigated by many authors until the present day. Wu [6] presented acoustical tweezers using two collimated focused ultrasonic beams propagating along opposite direction, which can trap latex particles of 270 μm diameter and clusters of frog eggs. S. B. Q. Tran [7] developed an acoustical tweezers using a slight frequency modulation of two ultrasound emitters to handle particles in a very controlled manner. Courtney [8] used an

M. Fei et al. (Eds.): LSMS/ICSEE 2017, Part I, CCIS 761, pp. 199–207, 2017.
DOI: 10.1007/978-981-10-6370-1_20

electronically controlled acoustic tweezer consisting of a circular 64-element ultrasonic array to trap 45 and 90-μm-diameter polystyrene spheres in larger regions. Kang [9] proposed an acoustics-vortex-based trapping model of acoustic tweezers and the maximum trapping force acting on a 13-μm polystyrene sphere in the produced acoustic vortex was 50.0 pN. Lee [10] calculated acoustic radiation force on a lipid sphere in a 100-MHz focused Gaussian field to demonstrate the acoustic tweezer effect near the focus. Shi [11] presented an active patterning technique of acoustic tweezers using standing surface acoustic wave (SSAW) to manipulate and pattern cells and microparticles. Hu [12] proposed an ultrasonic transducer to collect small particles by acoustic radiation surface of shaped ultrasonic tweezers. Other significant work in this area was reported [13–16].

In the above listed research, the acoustic trapping capability in various acoustic tweezers has been proposed and discussed. In order to manipulate heavier particle, the greater acoustic radiation force is required to be generated in practical applications. In this work, we proposed a method to increase the acoustic radiation force by optimizing a simple structure with two vibrating V-shaped metal strips [17]. The acoustic radiation force is generated by the leakage of a standing wave ultrasonic field in a triangular air gap and is opposite to the acoustic leakage direction. By punching symmetrical round holes at the bottom of the metal strips, it is found that the acoustic trapping capability increases with the change of ultrasonic field compared to the original structure. To calculate the acoustic radiation force with different strips situations in a complicated sound field, the analysis of finite element method (FEM) combined with the theory of acoustic radiation force is applied. The effects of the radius of holes, the position of holes at the bottom of the V-shaped strips and the arrangement of holes are clarified in detail.

2 Computational Model and Analysis Method

The original structure of the acoustic tweezers proposed by the authors' research group [18] is shown in Fig. 1. The metal strips made of aluminum have the shape and size shown in Figs. 1(a) and (b).

In the experiment, two identical aluminum strips are clamped to a Langevin transducer through a 10-mm-diameter hole in the upper part of the strips. The upper part is a rectangular aluminum plate with a size of $40 \times 45 \times 1.5$ mm. The lower part of the structure is a V-shaped aluminum strip with a length of 99 mm, width of 22.5 mm and thickness of 1.5 mm at the top. The lower part aluminum strip is tapered off from the upper end to the lower end and the thickness of strip at the tip is around 200 μm. As a consequence, a triangular air gap is formed between the two V-shaped strips with a thickness of 1.3 mm at the tip. A flexural vibration is excited in the aluminum strips by the ultrasonic transducer with a resonance frequency of 25.3 kHz. An acoustic radiation force used to suck the particles to the lower end of strips is generated by the sound filed near the lower end of the gap, which is formed by the flexural vibration [18].

To maximize the trapping capability, a round hole which is located at the center of the bottom of each metal strip is punched on each strip by changing the vibration mode, compared to the original structure. As shown in Fig. 1(c), it is 1 mm from the bottom of

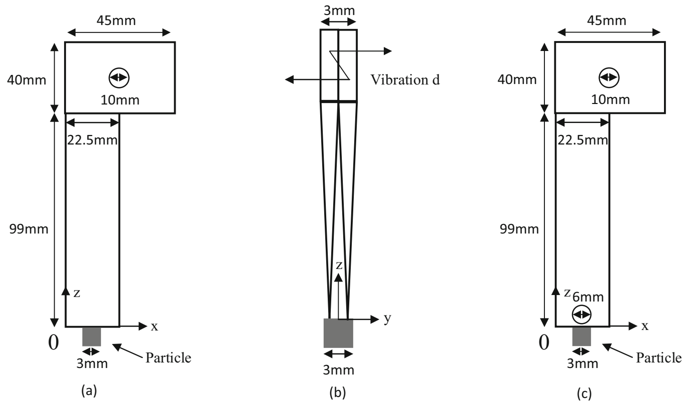

Fig. 1. Structure and size of acoustic tweezers. (a) Shape and size of the metal strip of original acoustic tweezers. (b) Air gap formed by the two V-shaped strips. (c) Shape and size of improved acoustic tweezers.

round hole with a radius of 3 mm to the bottom edge of the aluminum strip. The center of the hole is on the central line of the lower part of the metal strip in *xz*-plane.

The following integration over the surface of the object is used to calculate the acoustic radiation force F on a rigid immovable object in an ultrasonic field in ideal fluid [19].

$$F = \left\langle \iint_S (K - U)\mathbf{n}sdS \right\rangle. \tag{1}$$

where the notation $\langle\ \rangle$ denotes time average over one period, K is the kinetic energy destiny, U is the potential energy density and $\mathbf{n}$ is the outward normal unit vector of the surface. The following formulas are used to calculate the kinetic and potential energy densities K and U [20].

$$K = \frac{\rho_0 v^2}{2}. \tag{2}$$

$$U = \frac{p^2}{2\rho_0 c_0^2}. \tag{3}$$

where ρ_0 and c_0 are the density of and sound speed in the fluid, v is the velocity and p is the sound pressure.

Our computation of acoustic radiation force is implemented by the FEM software COMSOL Multiphysics for the sound field surrounding the 3 × 3 × 3 mm cube particle under the two vibrating sharp edges in air. The excitation frequency f applied to the structure model is 25.3 kHz, which is the resonance frequency of the transducer in the experiment. A prescribed displacement condition is added to the upper part of metal plates and then the amplitude of the y-direction vibration displacement (0-peak) d is set to 10 μm. In the computational model, an air domain with a size of $25 \times 20 \times 15$ mm is added as the sound field, where all the sound filed boundaries are radiation boundary. A cube particle with six sound hard boundaries is located below the bottom vibrating edges of the metal strips and the distance between the upper surface of the cube particle and the strip edges is 0.05 mm. Figure 2(a) shows the mesh of the structure mode in 3-D FEM calculation, where the minimum mesh size is 0.05 mm and the maximum mesh size at the surface boundaries is 0.8 mm, which is around 0.58% of the wavelength.

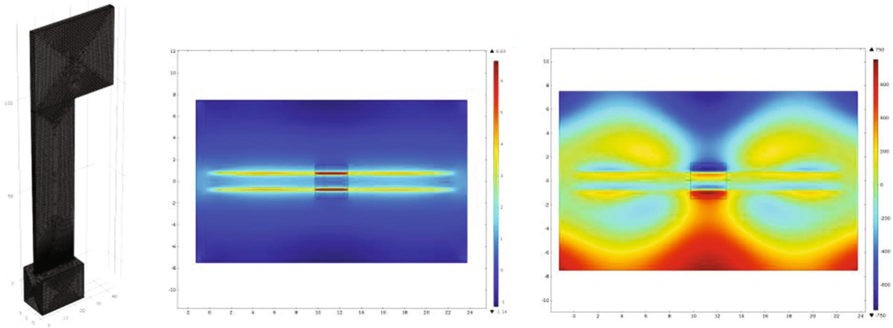

Fig. 2. 3-D FEM analyses of the structure model with a 3-mm-radius hole at the bottom area of the vibrating strips in air. (a) Mesh of the structure model. (b) The y-direction velocity on top surface of the particle. (c) The sound pressure on top surface of the particle.

The kinetic energy and potential energy of the original structure model with no round holes are calculated as the reference data. The computation process consists of two steps. In the first step, the velocity and sound pressure on top surface of the particle are solved by the acoustic module of the software shown in Figs. 2(a) and (b). In the second step, the kinetic and potential energy K and U is calculated by the Eqs. (2) and (3) through the post processing function of the software, which generate the acoustic radiation force. From the 3-D FEM results, it is known that $\iint_S \langle K \rangle dS$ and $\iint_S \langle U \rangle dS$ on the top surface of the cube particle are calculated to be 6.47×10^{-4} N and 1.87×10^{-5} N, respectively. The acoustic radiation force acting on a cube particle is determined by the force on the top surface of the particle and pointing upward, as the kinetic energy and potential energy on the side and bottom surfaces are less than 1% of that on the top surface.

3 Results and Discussion

As the cube particle is trapped at the center of the metal strip's edge in xz plane, the effect of radius of a single round hole on the acoustic radiation force is investigated. The hole's radius is ranging from 1 mm to 6 mm, which is on the center line of metal plates with 1 mm away from the bottom edges as shown in the Figs. 3(a) and (b). From the FEM computational results, it is found that the kinetic energy is almost 10 times the potential energy therefore the acoustic radiation force is mainly determined by the velocity on the top surface of the particle. If the vibrational velocity at the bottom edges of the metal strips increases, the acoustic radiation force is also strengthened. The y-direction velocities at the center line on inner side of one metal plate is shown in Fig. 3(c) when the radius of hole is less than 2.5 mm, and the voids in the figure indicate the position of hole on the strip. It is seen with the increase of the radius of the hole, the velocity at bottom edges decreases correspondingly. The computational acoustic radiation force *F* of acoustic tweezers with a single hole of radius less than 4.5 mm is shown in Fig. 3(d). It is found that by punching a small hole (radius less than 4.5 mm) in the bottom area of strips can't increase the acoustic trapping capability and even decrease the radiation force. Figure 3(e) shows the y-directional velocities at the center line when the radius of the hole is larger than 5 mm. The vibrational mode changes significantly compared with Fig. 3(c). In the radius range of 5 ~ 6 mm, the acoustic radiation force is strengthened compared with the original acoustic tweezers, and it decreases as the radius increasing shown in Fig. 3(f). The acoustic radiation force reaches its maximum when the hole's radius is 5 mm, which is 4 times of that with no hole on the strip. The

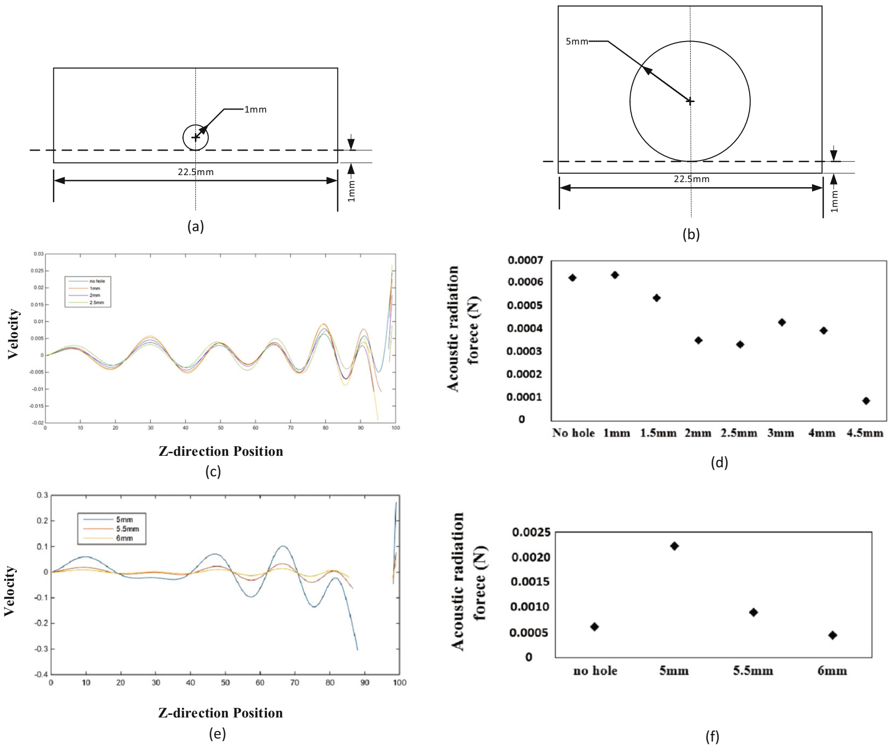

Fig. 3. The effect of hole's size on the vibration velocity and acoustic radiation force. (a - b) Position and size of a single hole. (c) The y-direction velocities at the center line of metal plates when the hole's radius is less than 2.5 mm. (d) The acoustic radiation force with hole's radius less than 4.5 mm. (e) The y-directional velocities at the center line with hole's radius larger than 5 mm. (f) The acoustic radiation force when the hole's radius is larger than 5 mm.

original acoustic tweezers is in flexural vibration. This vibration changes to be coupling with the radial vibration when punching a hole on the metal strip. The change in vibration mode causes the change of resonance of the acoustic tweezers, which leads to change in acoustic radiation force.

The effect of the number of the round hole on the acoustic radiation force is discussed in the Fig. 4. Two holes are symmetrically located about the center line of the lower metal plates and 1 mm away from each other as shown in Fig. 4(a). The vibrational modes and velocities of acoustic tweezers with two holes with radius more than 3.5 mm are shown in Fig. 4(b). The acoustic radiation force acting on the upper surface of the cube particle under two vibrating shape edges of the strips with two round holes is calculated by FEM software shown in Fig. 4(c). The radii of the round hole are all larger than 3.5 mm. The acoustic radiation force doesn't increase when the radius of hole is less than 3.5 mm compared with no holes case. In the condition that the radii of holes are 3.5 mm ~ 4.25 mm, the acoustic radiation forces generated by the two sharp edges of the strips with two round holes are obvious larger than that by the structures with only one hole and no hole. The acoustic radiation force reaches its maximum when the radii of two holes are 3.5 mm, which is 5.7 times of that with one hole with the radius of 5 mm on the strip, and 20 times of that with original acoustic tweezers.

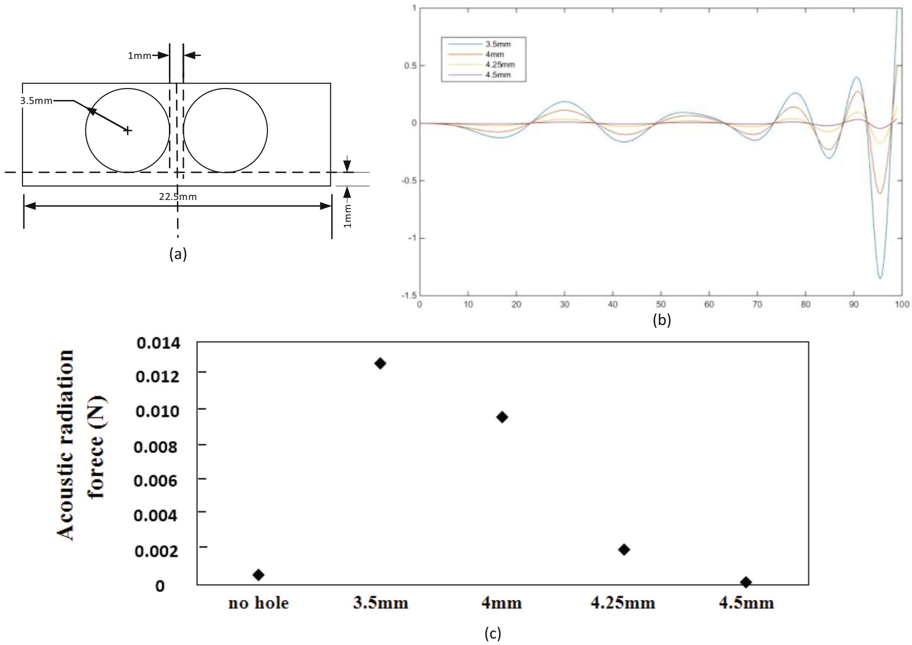

Fig. 4. (a) The size and position of two holes with radii of 3.5 mm. (b) The y-direction velocities at the center line of metal plates when the radii of two holes are more than 3.5 mm. (c) The calculated acoustic radiation force when the radii of two holes are more than 3.5 mm.

The effect of hole array on the acoustic trapping capability is also discussed in our works shown in Fig. 5. There are seven 1 mm-radius holes in a row on the bottom area of the metal strips and every single row is 1 mm away from the adjacent row shown in Fig. 5(a). The acoustic radiation forces is calculated for the different conditions with one, two and three rows of hole array on the strip, which is shown in Fig. 5(b). Adding more rows of round holes in the bottom area of metal strips can increase the velocity of the metal edges shown in Fig. 5(c), which leads to the significant improvement of the acoustic trapping capability. It is seen that from row number one to three, the acoustic radiation force on top surface of a particle increases correspondingly.

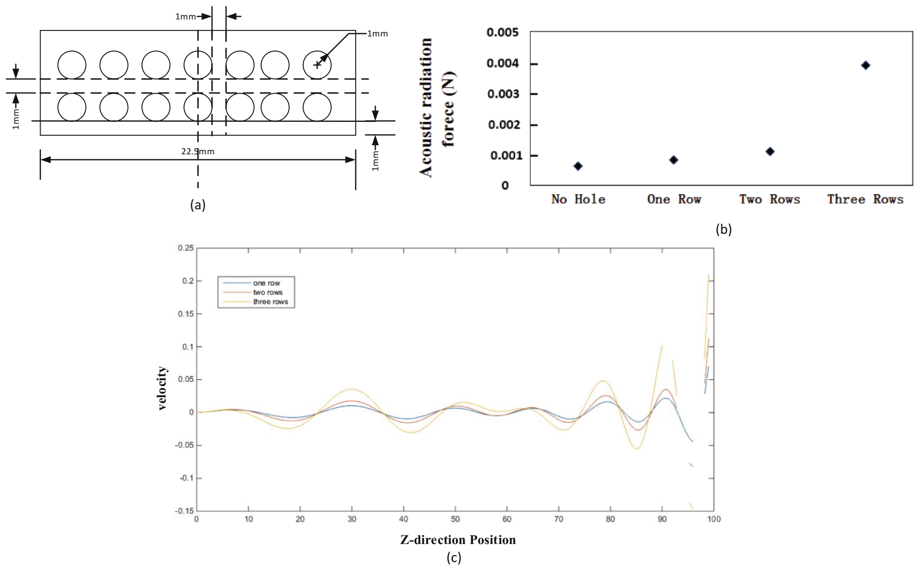

Fig. 5. (a) The size and position of two rows of hole array with radii of 1 mm. (b) The calculated acoustic radiation forces under the conditions of one, two and three rows of hole array on the metal strips. (c) The velocities of the center line with different rows of holes.

4 Conclusion

In summary, we proposed and explored a method to improve the acoustic trapping capability by punching specific round holes on acoustic tweezers, in which the acoustic radiation force is generated by the two vibrating V-shaped metal strips. Combining the FEM analysis and theory of acoustic radiation force, the effects of the radius of the round holes, the number and the arrangement of holes on the acoustic radiation force acting on particles are investigated by the COMSOL software. The acoustic radiation force is principal decided by the kinetic energy generated by the acoustic field, and the kinetic energy is influenced by the velocity of the metal strips. By punching the hole on the acoustic tweezers, the original flexural vibration couples with radial vibration in the direction of the radius of the hole, which causes the change in resonance of the structure.

When the hole's radius is less than 5 mm in only one hole condition, the trapping capability doesn't increase by punching a small round hole. When the hole's radius is larger than 5 mm, the velocity of metal strips and acoustic radiation force obviously increase compared with the original acoustic tweezers. The acoustic radiation force is maximum when the radius of hole is 5 mm. It is also found that the acoustic radiation force of acoustic tweezers with two holes on the bottom area of metal strips is significantly strengthened compared to that with original acoustic tweezers, if the radii of two holes are larger than 3.5 mm. By increasing the number of row of holes in vertical direction, there is obvious improvement on the acoustic radiation force even for the small radius holes.

Acknowledgement. This work is supported by Shanghai Young Eastern Scholar Talent Program (QD2015030).

References

1. Doblhoff-Dier, O., Gaida, T., Katinger, H., et al.: A novel ultrasonic resonance field device for the retention of animal cells. J. Biotechnol. Prog. **10**(4), 428–432 (1994)
2. Kosmala, A., Zhang, Q., Wright, R., et al.: Development of high concentrated aqueous silver nanofluid and inkjet printing on ceramic substrates. J. Mater. Chem. Phys. **132**(2–3), 788–795 (2012)
3. Ambedkar, B., Nagarajan, R., Jayanti, S.: Ultrasonic coal-wash for de-sulfurization. J. Ultrason. Sonochem. **18**(3), 718–726 (2011)
4. Castillo, J., Dimaki, M., Svendsen, W.E.: Manipulation of biological samples using micro and nano techniques. J. Integrative Biol. **1**(1), 30–42 (2009)
5. Lee, C., Lee, J., Lau, S.T, et al.: Single microparticle manipulation by an ultrasound microbeam. In: IEEE International Ultrasonics Symposium, pp. 849–852. IEEE Press (2010)
6. Wu, J.: Acoustical tweezers. J. Acoust. Soc. Am. **89**(5), 2140–2143 (1991)
7. Tran, S.B.Q., Marmottant, P., Thibault, P.: Fast acoustic tweezers for the two-dimensional manipulation of individual particles in microfluidic channels. J. Appl. Phys. Lett. **101**(11), 1109–1111 (2012)
8. Courtney, C.R.P., Demore, C.E.M., Wu, H., et al.: Independent trapping and manipulation of microparticles using dexterous acoustic tweezers. J. Appl. Phys. Lett. **104**(15), 154103 (2014)
9. Kang, S.T., Yeh, C.K.: Potential-well model in acoustic tweezers. J. IEEE Transactions on Ultrasonics Ferroelectrics & Frequency. Control **57**(6), 1451–1459 (2010)
10. Lee, J., Shung, K.K.: Radiation forces exerted on arbitrarily located sphere by acoustic tweezer. J. Acoust. Soc. Am. **120**(2), 1084–1094 (2006)
11. Shi, J., Ahmed, D., Mao, X., et al.: Acoustic tweezers: patterning cells and microparticles using standing surface acoustic waves (SSAW). J. Lab Chip **9**(20), 2890–2895 (2009)
12. Hu, J., Santoso, A.K.: A /spl pi/-shaped ultrasonic tweezers concept for manipulation of small particles. J. IEEE Transactions on Ultrasonics Ferroelectrics & Frequency. Control **51**(11), 1499–1507 (2004)
13. Gesellchen, F., Bernassau, A.L., Déjardin, T., et al.: Cell patterning with a heptagon acoustic tweezer–application in neurite guidance. J. Lab Chip **14**(13), 2266–2275 (2014)
14. Mitri, F.G.: Radiation force of acoustical tweezers on a sphere: The case of a high-order Bessel beam of quasi-standing waves of variable half-cone angles. J. Appl. Acoust. **71**(5), 470–472 (2013)

15. Hu, J., Yang, J., Xu, J.: Ultrasonic trapping of small particles by sharp edges vibrating in a flexural mode. J. Appl. Physics Lett. **85**(24), 6042–6044 (2004)
16. Hu, J., Xu, J., Yang, J., et al.: Ultrasonic collection of small particles by a tapered metal strip. J IEEE Trans Ultrason Ferroelectr Freq Control **53**(3), 571–578 (2006)
17. Liu, Y., Hu, J.: Trapping of particles by the leakage of a standing wave ultrasonic field. J. Appl. Phys. **106**(3), 034903 (2006)
18. Liu, Y., Hu, J., Zhao, C.: Dependence of acoustic trapping capability on the orientation and shape of particles. IEEE Trans. Ultrason. Ferroelectr. Freq. Control **57**(6), 1443–1450 (2010)
19. Morfey, C.L.: Dictionary of Acoustics. Academic Press, San Diego, pp. 14–15 (2000)
20. Hasegawa, T., Kido, T., Iizuka, T., et al.: A general theory of Rayleigh and Langevin radiation pressures. J. Acoust. Soc. Jpn. **21**(3), 145–152 (2000)