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Acoustic levitation of an object larger than the acoustic wavelength

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Levitation and manipulation of objects by sound waves have a wide range of applications in chemistry, biology, material sciences, and engineering. However, the current acoustic levitation techniques are mainly restricted to particles that are much smaller than the acoustic wavelength. In this work, it is shown that acoustic standing waves can be employed to stably levitate an object much larger than the acoustic wavelength in air. The levitation of a large slightly curved object weighting 2.3 g is demonstrated by using a device formed by two 25 kHz ultrasonic Langevin transducers connected to an aluminum plate. The sound wave emitted by the device provides a vertical acoustic radiation force to counteract gravity and a lateral restoring force that ensure horizontal stability to the levitated object. In order to understand the levitation stability, a numerical model based on the finite element method is used to determine the acoustic radiation force that acts on the object.
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I. INTRODUCTION

The contactless suspension of matter by acoustic fields is called acoustic levitation[1] and it has many potential applications in biology,[2] material sciences,[3,4] analytical chemistry,[5,6] and in microassembly.[7,8] Acoustic levitation can be used to suspend small particles,[9,10] liquid drops,[11,12] and even small living animals[13,14] in air.

There are different approaches to acoustically levitate objects in air. The most common method is to use acoustic standing waves. A typical standing wave device, usually referred to as single-axis,[9,10] consists of a circular transducer and a reflector, which are arranged coaxially and separated by a certain distance such that a standing wave of high pressure amplitude is established between them. Despite the simplicity of single-axis acoustic levitators, it is only capable of levitating small particles at fixed positions in space. To overcome this limitation, acoustic levitation devices formed by multiple transducers were used to levitate and manipulate particles through air.[15–17]

Another approach is the single-beam trapping,[17,18] in which small particles can be levitated and manipulated by using a single-sided array of transducers. In contrast to the levitation and manipulation based on standing waves, the use of single-beams allows trapping small particles without requiring the particles to be confined between a sound emitter and a reflector or between two emitters.

Despite the recent advances in acoustic levitation and contactless acoustic manipulation, the current strategies are mainly restricted to particles and objects that are much smaller than the acoustic wavelength. A technique capable of levitating large objects is the near-field levitation,[19] in which planar objects can be levitated at a distance of tens of micrometers from a vibrating surface. However, in this technique, the maximum levitation height is limited to few hundreds of micrometers from the vibrating surface. The acoustic levitation of large objects at a considerable distance from the transducers has been demonstrated only in very specific cases such as acoustic levitation of a planar object,[20] a thin elongated object,[15] and a large sphere.[21] The challenge of levitating an object larger than the acoustic wavelength relies in generating both an acoustic radiation force to counteract gravity and a horizontal restoring force to stabilize the object in air.

The working principle of a typical standing wave device, called single-axis,[9,10] is illustrated in Fig. 1(a). In this device, an acoustic standing wave is established between a sound emitter and a concave reflector, in which a small particle is trapped around the pressure node due to the action of the acoustic radiation force.[3,10] The acoustic force behavior in the neighborhood of a pressure node is similar to the restoring force of a spring.[22,23] For small distances from the pressure node, the acoustic radiation force F_{rad} acting on a small particle is proportional to its distance from the pressure node. Therefore, in the presence of gravity, a small particle levitates slightly below the pressure node such that the gravitation force F_g is counterbalanced by the acoustic restoring force F_{rad}.

One interesting point in Fig. 1(a) is that the standing wave generates a radiation force not only on the levitated particle but also on the reflector. If the reflector is replaced by a large object, the acoustic radiation force can be used to

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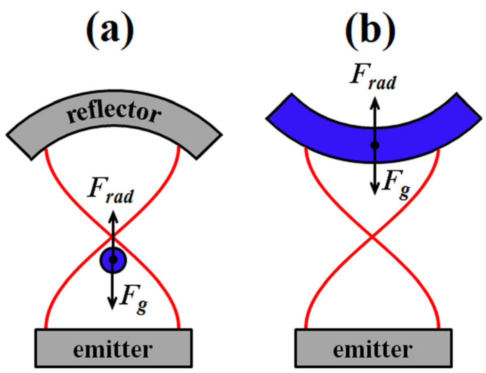

FIG. 1. (Color online) (a) Typical configuration of an acoustic levitation device. (b) Acoustic levitation of an object larger than the acoustic wavelength.

counteract gravity and suspend the object in air,[20,21] as is illustrated in Fig. 1(b). However, a successful levitation also requires horizontal restoring forces to prevent the object from escaping laterally. In the paper of Zhao and Wallaschek,[20] in which they demonstrated the acoustic levitation of a compact disk, the levitation device was not capable of providing radial restoring forces and a central pin was used for centering the compact disk in the radial direction. Recently, we have demonstrated the acoustic levitation of a large solid sphere in air.[21] In this demonstration, we used three ultrasonic transducers arranged in a tripod fashion to achieve both vertical and horizontal stability.

In this paper, we show that an acoustic standing wave can be applied to suspend a curved object larger than the acoustic wavelength in air. We also demonstrate that if the standing wave is formed between the emitter and the convex surface of the object, a lateral acoustic restoring force arises, providing horizontal stability to the levitated object. To understand the physics behind the acoustic levitation, the vertical and horizontal acoustic radiation forces acting on the levitated object are determined numerically.

II. ACOUSTIC LEVITATION DEVICE

The acoustic levitation of a curved object larger than the acoustic wavelength is carried out with the device illustrated in Fig. 2(a). This device is formed by two custom-made 25 kHz Langevin piezoelectric transducers and an aluminum rectangular vibrating plate with 300 mm in length, 71 mm in width, and 2 mm in thickness. The transducers are formed by two piezoelectric rings (PZT-4, with 6.35 mm in thickness, external diameter of 38.1 mm and internal diameter of 12.7 mm) sandwiched between two aluminum masses by a central bolt. The transducers are connected to the aluminum plate by using two trapezoidal aluminum horns (height of 96.8 mm and parallel bases of 25.4 and 10 mm). This type of device is commonly employed in near field acoustic levitation, in which planar objects are levitated at a distance of tens of micrometers from a vibrating surface.[19]

The levitation principle is illustrated in Fig. 2(b). By electrically exciting the transducers at 25 kHz, a flexural standing wave with a wavelength λ_p is generated along the plate. The flexural vibration of the aluminum plate radiates a

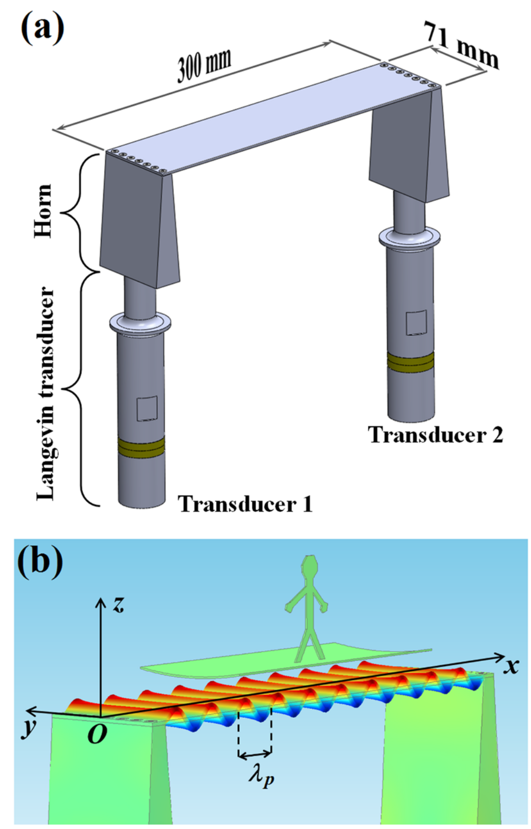

FIG. 2. (Color online) Levitation device and working principle. (a) Illustration of the acoustic levitation device, formed by two 25 kHz Langevin transducers connected and an aluminum plate. (b) Acoustic levitation principle. Movie Mm. 1 illustrates the vibration of the aluminum plate.

vertical sound wave in the air medium with a wavelength λ of 13.6 mm. By placing a slightly curved object at a distance of approximately a half wavelength from the vibrating plate, an acoustic standing wave is established in the air gap between the aluminum plate and the object, generating an acoustic radiation force capable of suspending the curved object in air.

III. NUMERICAL MODEL

A computational simulation based on the finite element method was implemented in order to calculate the acoustic radiation force acting on the levitated object. The numerical model was implemented in the software COMSOL Multiphysics and was divided into two complementary simulations. The first one simulates the Langevin transducers and the aluminum plate. It was performed to obtain the displacement amplitude distribution over the top surface of the vibrating aluminum plate when both transducers are excited at a frequency of 25 kHz. The aluminum parts were modeled by considering a density of 2700 kg/m^3, Young's modulus of 70×10^9 Pa, and Poisson's ratio of 0.33. According to the simulation, a flexural standing wave with a wavelength λ_p of 27.7 mm is produced along the plate. The flexural vibration of the aluminum plate at 25 kHz is shown in Fig. 2(b) and in a supplementary video (movie Mm. 1). The vertical displacement of the plate along the x axis is presented in Fig. 3. The vertical vibration $\xi(x, t)$ of the plate can be approximated by

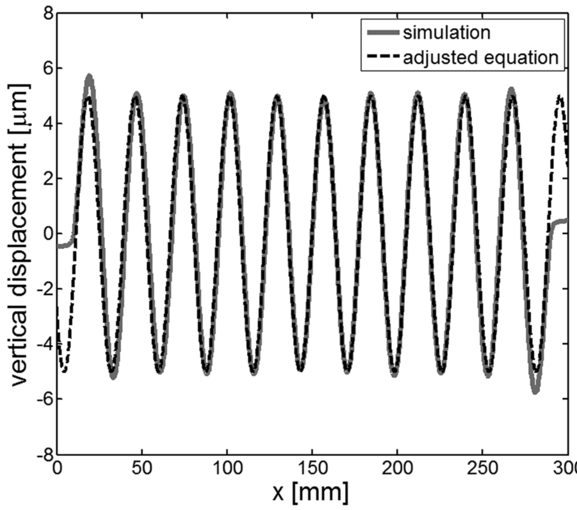

FIG. 3. Vertical displacement along the x axis of the aluminum plate at a frequency of 25 kHz.

$$\xi(x,t) = A \sin[(2\pi/L_x)x + \phi] \cos(\omega t), \tag{1}$$

where $L_x = \lambda_p = 27.7$ mm, $A = 5\,\mu$m is the maximum displacement amplitude, ϕ is the spatial phase, and ω is the angular frequency. As observed in Fig. 3, the vertical displacement distribution given by Eq. (1) is a very good approximation to describe the vibration behavior along the aluminum plate.

Mm. 1. Simulated flexural vibration of the aluminum plate. This is a file of type "mpg" (6.6 Mb).

The displacement amplitude distribution over the aluminum plate obtained with the first simulation was used in the second one to obtain the acoustic pressure field p and the particle velocity distribution $\mathbf{u}$ in air. The geometry of the acoustic simulation is presented in Fig. 4, where H is the distance between the aluminum plate and the bottom part of the curved object. In this simulation, an air density of 1.2 kg/m^3 and a sound velocity of 343 m/s were considered. The width of the vibrating aluminum plate and the levitated object is $L_y = 71$ mm and it was considered that the levitated object has a curvature radius of 300 mm. To reduce the computational time, only a small section (Fig. 4) corresponding to one wavelength $L_x = \lambda_p$ was simulated and periodic boundary conditions were applied at $x = 0$ and $x = L_x = \lambda_p = 27.7$ mm. Periodic boundary conditions can be applied when the object length is much larger than the levitation height, which is a reasonable assumption for the object considered herein. However, it is worth mentioning that this strategy is useful to obtain the pressure field in the middle section of the object, since edge effects at the two ends are neglected. To simplify the analysis, the levitated object was modeled as rigid material. It was also considered that the top surface of the aluminum plate vibrates harmonically with vertical displacement amplitude given by $\xi(x) = A \sin[(2\pi/L_x)x]$, with $A = 5\,\mu$m and $L_x = 27.7$ mm. Perfectly matched layers (PML) were employed to prevent wave reflections at the edges of the air domain. Using COMSOL, the linear acoustic fields p and $\mathbf{u}$ were obtained in the air gap between the transducer and the reflector.

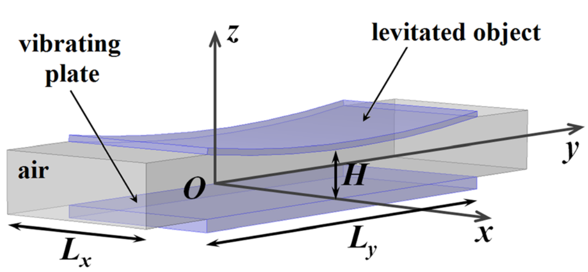

FIG. 4. (Color online) Three-dimensional acoustic model used to calculate the pressure field in air.

The acoustic radiation force acting on the levitated object can be calculated by integrating the time-averaged acoustic radiation pressure $\langle p_r \rangle$ over the object surface. As demonstrated elsewhere,[24] the radiation pressure is a nonlinear phenomenon, but it can be derived from the linear acoustic pressure p and the linear particle velocity $\mathbf{u}$. From these fields, the time-averaged acoustic radiation pressure $\langle p_r \rangle$ is calculated by[24,25]

$$\langle p_r \rangle = \frac{1}{2\rho_0 c_0^2} \langle p^2 \rangle - \frac{\rho_0 \langle \mathbf{u} \cdot \mathbf{u} \rangle}{2}, \tag{2}$$

where the angle brackets $\langle\rangle$ represent the time-average over a period, ρ_0 is the fluid density and c_0 is the sound velocity in the fluid medium. Finally, the acoustic radiation force $\mathbf{F_{rad}}$ on the object is determined by using

$$\mathbf{F_{rad}} = \int_{S_0} \langle p_r \rangle \mathbf{n} dS, \tag{3}$$

where S_0 is the integration surface and $\mathbf{n}$ is the surface normal vector. In this paper, the z and y components of the acoustic radiation force $\mathbf{F_{rad}}$ are denoted by F_z and F_y, respectively. As the simulation was performed in a small section of the levitated object ($L_x = 27.7$ mm), the total acoustic radiation force that acts on a levitated object of length L is calculated by multiplying $\mathbf{F_{rad}}$ by L/L_x.

IV. EXPERIMENT

The acoustic levitation device illustrated in Fig. 2(a) is used to levitate a curved object larger than the acoustic wavelength. The transducers' signals are provided by a dual-channel function generator (33500B, Agilent Technologies Inc., Santa Clara, CA) and amplified by two 800A3A power amplifiers (Amplifier Research Corp., Souderton, PA). The maximum displacement amplitude along the plate was measured by a Laser Doppler Vibrometer (OFV-534 Sensor Head with an OFV-5000 controller, Polytec GmbH, Germany) and adjusted to 5 μm.

To demonstrate the device levitation capability, an object weighting 2.3 g was fabricated using cardstock paper. The bottom part of the object was made with a curved sheet of 170 mm in length, 71 mm in width, and a curvature radius in the order of 300 mm. A second part of the object, resembling a human figure with a height of approximately 85 mm, was attached to the bottom part. As shown in Fig. 5, the acoustic radiation force due to the standing wave generated between the aluminum vibrating plate and the bottom of the object is capable of suspending the object in air, at a height of approximately 9 mm from the vibrating plate. As it can be seen in Fig. 5, the sound wave provides a vertical acoustic radiation force to suspend the object and lateral restoring forces to prevent the object from falling laterally. A supplementary video (Movie Mm. 2) demonstrates the acoustic levitation of the object.

Mm. 2. Video showing the acoustic levitation of a curved object weighting 2.3 g. This is a file of type "mpg" (13.9 Mb).

V. RESULTS AND DISCUSSION

The acoustic model of Fig. 4 was used to calculate the acoustic pressure distribution p for different values of H. The simulated acoustic pressure distribution in the air gap between the vibrating plate and the levitated object for a levitation height H of 7.9 mm is shown in Fig. 6. The acoustic pressure amplitude in the air gap between the aluminum plate and the levitated object along the dashed line of Fig. 6(c) is presented in Fig. 6(d). The acoustic pressure amplitude of Fig. 6 shows that an acoustic standing wave is formed between the vibrating aluminum plate and the levitated object.

Mm. 3. Animation of the acoustic pressure distribution in the air gap between the aluminum plate and the levitated object. This is a file of type "mpg" (2.7 Mb).

The simulated vertical acoustic radiation force F_z on the 2.3 g curved levitated object as a function of H is shown in Fig. 7(a). This figure presents two peaks, with the first at $H = 7.16$ mm and the second at $H = 7.90$ mm. The first peak is due to the formation of acoustic standing waves close to the edges of the levitated object and the larger peak at $H = 7.9$ mm is due to the standing wave established in the

FIG. 5. (Color online) Acoustic levitation of a curved object weighting 2.3 g. A supplementary video (Movie Mm. 2) shows the acoustic levitation of the curved object.

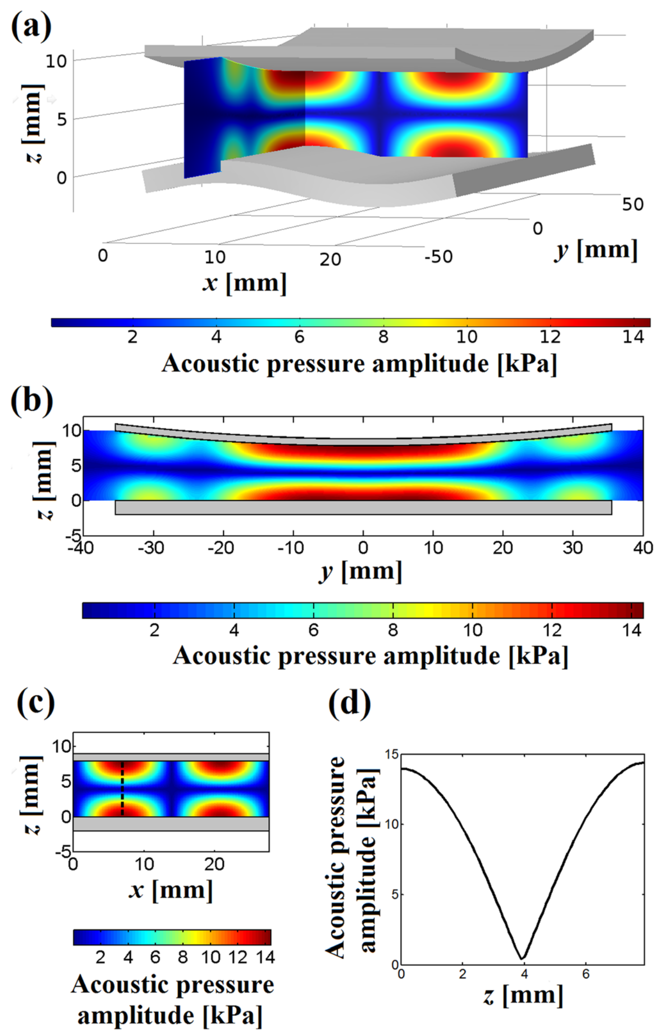

FIG. 6. (Color online) Computational simulation of the acoustic pressure for $H = 7.9$ mm. (a) Acoustic pressure amplitude in the air gap between the levitated object and the flexural vibrating plate (see Movie Mm. 3). The pressure amplitude is presented in two different planes: xz-plane and yz-plane located at $x = L_x/4$. (b) Acoustic pressure amplitude over a yz-plane located at $x = L_x/4$. (c) Acoustic pressure amplitude over a xz-plane located at $y = 0$. (d) Acoustic pressure amplitude over the dashed line of (c).

central region of the air gap [see Fig. 6(b)]. In the hypothesis of an acoustic plane wave, there would be a peak located at a height $H = \lambda/2 = 6.8$ mm. However, as the acoustic wave emitted by the vibrating aluminum plate is not a plane wave, the resonance occurs at a height H slightly higher than $\lambda/2$.[10] The curve of Fig. 7(a) allows predicting the levitation height of the 2.3 g object. As observed in Fig. 7(a), the vertical equilibrium is reached when the gravitational force acting on the 2.3 g object is counterbalanced by the acoustic radiation force. For a 2.3 g object, the equilibrium occurs at a levitation height of 8.25 mm from the flexural vibrating plate. This value is in a reasonable agreement with the levitation height of approximately 9 mm obtained experimentally.

The levitation of a large object in air requires not only a vertical radiation force F_z to counteract gravity but also a horizontal restoring force, F_y. The force F_z is responsible for the levitation of the curved object while the force F_y is responsible for the lateral stabilization in air. Neglecting viscous shear stress, it is evident from Eq. (3) that if the object

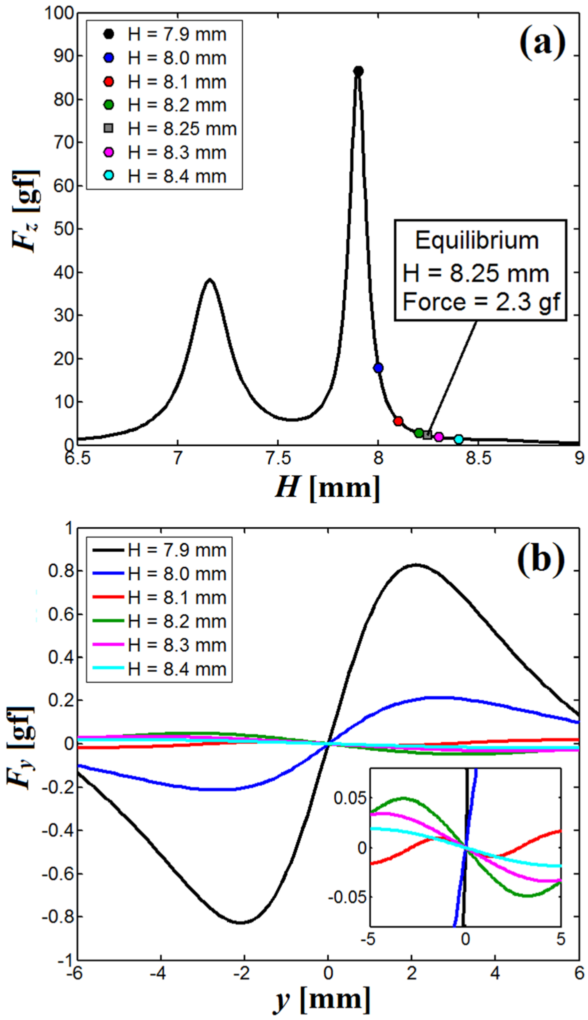

FIG. 7. (Color online) Acoustic radiation force on the levitated object. (a) Vertical acoustic radiation force F_z as a function of H. (b) Horizontal acoustic radiation force F_y as a function of the horizontal position y of the levitated object for different values of H.

is flat with its surface parallel to the aluminum plate, the surface normal vector **n** has only a z component. Therefore, no horizontal acoustic forces act on the object and lateral stabilization is not possible. By slightly curving the object, there will be lateral forces on the object which can be used to stabilize the object in air. We observed experimentally that a small curvature of the object is sufficient to provide lateral stabilization to the object. Although large curvatures increase lateral forces, they cause a decrease of the vertical acoustic radiation force. Therefore, we choose a small curvature to allow both high vertical force and a lateral force high enough to prevent the object from falling laterally.

The horizontal acoustic radiation force F_y that acts on the curved levitated object is presented in Fig. 7(b). This figure shows the horizontal force as a function of the horizontal position y of the levitated object for different values of H. For values of H of 7.9 and 8.0 mm, the curves present a positive slope at $y = 0$ (unstable equilibrium). Consequently, if a small perturbation moves the levitated object laterally, the horizontal force increases in the direction of the lateral displacement, causing the object to fall laterally. However, for H varying from 8.1 to 8.5 mm, the curves present a negative slope (stable equilibrium), and the lateral acoustic force becomes a restoring force. This means that if the object moves laterally, a restoring acoustic radiation force moves the object back to its equilibrium position.

In order to understand how the acoustic field produces a lateral restoring force on the levitated curved object, Fig. 8 presents the acoustic pressure distribution when the object is located at $y = 0$ and $y = 2$ mm. When the levitation height is $H = 8$ mm and the object's center of mass is located at $y = 0$ [Fig. 8(a)], the acoustic pressure amplitude under the object is almost uniform from $y = -20$ mm to $y = +20$ mm. If the object is laterally displaced to $y = +2$ mm [Fig. 8(b)], the acoustic pressure amplitude on the left side of the object is higher than on the right side, producing a lateral acoustic force F_y that pushes the object out of the levitator. For a levitation

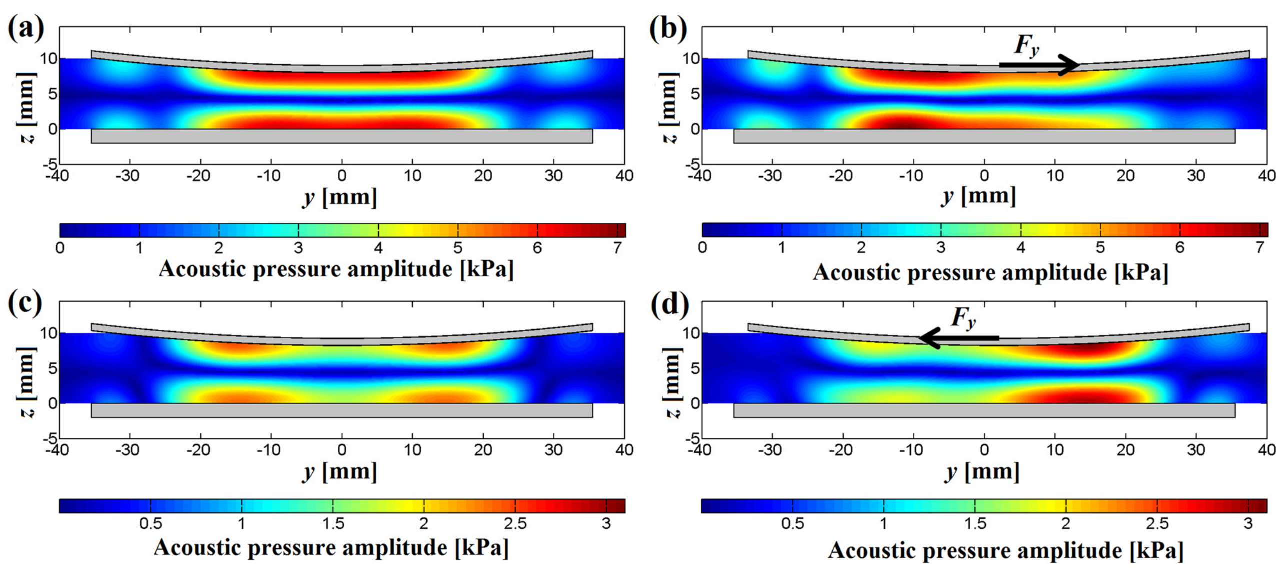

FIG. 8. (Color online) Acoustic pressure distribution over a yz-plane located at $x = L_x/4$. (a) $H = 8$ mm with the object located at $y = 0$. (b) $H = 8$ mm with object located at $y = 2$ mm. (c) $H = 8.25$ mm with the object located at $y = 0$. (d) $H = 8.25$ mm with object located at $y = 2$ mm.

height of $H = 8.25$ mm and the object located at $y = 0$, there are two positions ($y \approx -15$ mm and $y \approx +15$ mm) of maximum acoustic pressure amplitude under the object surface [Fig. 8(c)]. When the object is displaced to $y = +2$ mm, there is an increase of the pressure amplitude at $y \approx +15$ mm and a pressure decrease at $y \approx -15$ mm [Fig. 8(d)]. This difference of pressure amplitudes on both sides produces a lateral restoring force F_y, which causes the object to return to its resting position ($y = 0$ mm). This simulation shows that if the bottom part of the levitated object has a convex shape, there is a horizontal restoring force in y direction, providing lateral stability to the levitated object. Although the levitation was demonstrated with a slightly curved object, the numerical analysis presented in this paper can also be applied to investigate the lateral stability of objects with complex shapes and different sizes.

The simulated results are in agreement with our experimental observations. According to Eqs. (2) and (3), the acoustic radiation force $\mathbf{F_{rad}}$ is proportional to the square of the acoustic pressure p, which in turn is proportional to the displacement amplitude of the vibrating aluminum plate. Consequently, by decreasing the displacement amplitude of the vibrating plate, the acoustic radiation force curve of Fig. 7 decreases, changing the equilibrium height from $H = 8.25$ mm to a lower value. If the displacement amplitude is decreased such that the new equilibrium position reaches $H \approx 8.0$ mm, the vertical acoustic radiation force is sufficient to counterbalance gravity and suspend the object. However, the lateral force becomes a non-restoring force, causing the object to fall laterally [Fig. 8(b)]. This is in agreement with our experimental results, in which we observed that the levitating object escapes laterally when the displacement amplitude of the aluminum plate is slowly decreased.

For small lateral displacements, the lateral acoustic restoring force that acts on the object is similar to the restoring force of a spring.[22,23] For our levitated object of 2.3 g, the levitation height predicted by the simulation is $H = 8.25$ mm. At this height the acoustic restoring force has an elastic constant $k = 0.16$ N/m. By making an analogy with a harmonic oscillator,[23] we can use this elastic constant and the mass $m = 2.3$ g of the levitated object to calculate the frequency $f = (1/2\pi)\sqrt{k/m}$ of the lateral oscillation, which gives a frequency of 1.3 Hz. This frequency is in reasonable agreement with the lateral frequency obtained experimentally. By analyzing a video of the levitated object we obtained a lateral oscillation frequency of approximately 0.8 Hz. This difference is attributed to some simplifying assumptions in the numerical model, such as neglecting acoustic radiation torques and considering that the wave is totally reflected by the levitated object. In addition, there are experimental uncertainties in the displacement amplitude of the vibrating plate and on the curvature radius of the object.

The numerical model was used to investigate the levitation stability in the y and z directions. According to the model, the radiation force in the x-direction is zero. Consequently, the object can move freely in x and we could expect the object would fall off the levitator when it reaches the extremities of the vibrating plate. However, it was experimentally verified that the object does not fall in the x-direction (see supplementary video Mm. 2 at time instant $t = 6$ s). One hypothesis to explain why this occurs is the slightly increase of the displacement amplitude near the ends of the vibrating plate. According to Fig. 3, the displacement amplitude at $x \approx 20$ mm and $x \approx 280$ mm is slightly higher than in the middle section. Our hypothesis is hence that this increase of the displacement amplitude could result in a force that prevents the object from falling in the x-direction. In any case, this hypothesis has not been verified yet, and as a future work we want to investigate if this hypothesis is correct.

VI. CONCLUSIONS

In summary, we demonstrated that an object larger than the acoustic wavelength can be acoustically levitated by generating an acoustic standing wave between a vibrating plate and the object itself. Using computational simulations, we showed that the acoustic standing wave produces a vertical acoustic radiation force capable of counteracting gravity and suspending the object in air. Moreover, the simulations showed that, due to the curved shape of the object, a horizontal acoustic restoring force arises for certain levitation heights. This force provides lateral stability to the object, preventing it from falling laterally. Although the levitation was demonstrated for a very specific geometry of the levitated object, we believe that the methodology presented herein can be easily extended to allow not only the levitation but also the manipulation of large objects in air.

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