ACOUSTIC LEVITATION OF LARGE OBJECTS IN AIR

Marco A. B. Andrade

University of São Paulo, Institute of Physics, São Paulo, Brazil
email: marcobrizzotti@gmail.com

Anne Bernassau

Heriot-Watt University, School of Engineering and Physical Sciences, Edinburgh, UK,

Fábio T. A. Okina and Julio C. Adamowski

University of São Paulo, Polytechnic School, São Paulo, Brazil,

Sound waves can be used to levitate solid particles and liquid drops in air. However, most acoustic levitation methods are only capable of levitating objects considerably smaller than the acoustic wavelength. In this paper, we present an acoustic method to levitate objects much larger than the acoustic wavelength. In this method, a large object is suspended in air by producing an acoustic standing wave between a set of ultrasonic transducers and the object. To demonstrate this levitation method, a sphere of 50 mm in diameter is suspended in air by three 25 kHz transducers arranged in a tripod fashion and a slightly curved object is acoustically levitated by using a single transducer operating at 24.57 kHz. The acoustic levitation of large objects is simulated by using the Finite Element Method to calculate the acoustic pressure and velocity fields around the object. From these fields, the acoustic radiation pressure is calculated and the vertical and horizontal forces that act on the object are determined by numerically integrating the radiation pressure over the surface of the objects.
Keywords: acoustic levitation, acoustic radiation force, finite element method

1. Introduction

Sound waves carry linear momentum [1] and transferring it to an object results in an acoustic radiation force [2], which can be used to levitate [3] and manipulate [4,5] matter in air.

There are different approaches to acoustically levitate objects in air. One of the most usual strategies consists in trapping small objects in the pressure nodes of a standing wave field established between a transducer and a reflecting surface [6,7]. Another well-known technique is called near-field (also called squeeze film) levitation. In this technique, flat objects can be levitated at a height of tens of micrometers from a surface vibrating at an ultrasonic frequency [8,9].

Recently, the acoustic levitation of small particles relying on single beams was demonstrated [10,11]. In one of these demonstrations, multiple transducers were used to levitate, manipulate and rotate small particles in air [10]. In another study [11], a collection of metamaterial bricks was placed in front of an array of transducers to shape the sound field in such a way that the emitted wave was capable of levitating small particles in air.

Despite the recent progresses in acoustic particle levitation and manipulation in air, most levitation strategies are restricted to particles [3,6] and liquid drops [12] that are much smaller than the acoustic wavelength. In contrast, near-field acoustic levitation [8] is capable of levitating and trans-

porting large objects, but the maximum levitation height is restricted to hundreds of micrometers from the transducer surface.

An acoustic approach for levitating objects larger than the acoustic wavelength was proposed by Zhao and Wallaschek [13]. In their approach, a planar object much larger than the acoustic wavelength is levitated by generating a standing wave between an ultrasonic transducer and the object. However, this approach was only capable of providing vertical acoustic forces to the levitated object and a central pin in contact with the object was necessary to prevent the object from falling laterally. To solve this problem, we have used three transducers arranged in a tripod configuration to achieve both vertical and lateral levitation stability [14]. By using three ultrasonic transducers operating at 25 kHz, we have levitated a 50-mm-diameter expanded polystyrene sphere without any physical contact between the transducers and the levitated sphere.

In most cases, multiple transducers are required to achieve both vertical and horizontal levitation stability of the large object in air. However, we show here that it is possible to suspend a large object in air using only one ultrasonic transducer. In this paper, two setups capable of levitating large objects are investigated. The acoustic levitation of large objects is simulated by using the Finite Element Method (FEM). The acoustic pressure and particle velocity distributions around the object are determined by using FEM. From these fields, the acoustic radiation pressure is calculated and integrated over the object surface to obtain the vertical and horizontal acoustic radiation forces that act on the object. To illustrate these distinct cases, two different objects are acoustically levitated in air.

2.   Levitation strategies

In order to acoustically levitate a large object, two conditions must be satisfied. The first condition is that the acoustic radiation force must be high enough to counteract gravity and suspend the object in air. The second condition involves generating a horizontal restoring force to prevent the object from escaping laterally. In this paper, two different acoustic levitation strategies satisfying these conditions are presented. Both strategies are based on generating an acoustic standing wave between transducers and the object.

The first levitation strategy is illustrated in Fig. 1(a) and it was described in a previous paper [14]. In the levitation strategy of Fig. 1(a), the gravity force $\mathbf{F_g}$ that acts on the object is counterbalanced by the acoustic radiation force $\mathbf{F_{rad}}$ produced by three ultrasonic transducers arranged in a tripod fashion. In this arrangement, each transducer applies an axial radiation force on the object and at least three transducers are required to provide vertical and horizontal levitation stability.
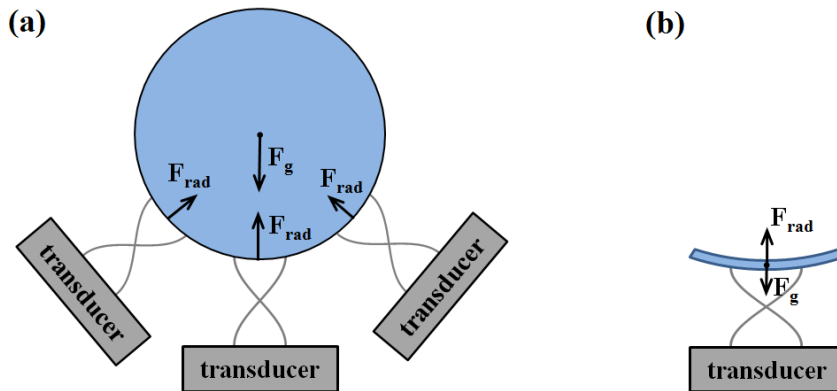

Figure 1: Acoustic levitation strategies to achieve vertical and horizontal stability: (a) Three transducers; (b) Single transducer.

The second strategy is shown in Fig. 1(b). This configuration requires only one ultrasonic transducer to provide vertical and horizontal restoring forces to the levitated object. In general, this con-

figuration is not capable of providing horizontal restoring forces to the levitated object, but there are specific object geometries in which the acoustic standing wave generates not only a vertical force on the object but also a horizontal restoring force. In this case, it is possible to use a single transducer to provide both vertical and horizontal levitation stability.

3.   Numerical models

The axial and lateral acoustic radiation forces that act on objects having axial symmetry are determined numerically by using the Finite Element Method. The axial force on an object aligned with the transducer's main axis is determined by axisymmetric models (Fig. 2). The numerical simulations are carried out in the software COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden). Using a linear acoustic model, the COMSOL software is used to obtain the acoustic pressure p and the particle velocity $\mathbf{u}$ around the object surface. It is assumed that the transducer circular face vibrates uniformly with a velocity amplitude u_0. Perfectly matched layers (PML) are applied at the edges of the air domain to simulate an infinite medium. The simulations are performed by considering an air density ρ_0 of 1.2 kg/m^3 and a sound velocity c_0 of 340 m/s. From the simulated linear fields p and $\mathbf{u}$, the time-averaged radiation pressure is calculated by [2,15]:

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

In Eq. (1), the symbol $\langle\ \rangle$ represents the time average. From the time-averaged radiation pressure $\langle p_r \rangle$, the acoustic radiation force vector $\mathbf{F_{rad}}$ that acts on the object is determined by:

$$\mathbf{F_{rad}} = -\int_{S_0} \langle p_r \rangle \mathbf{n}\, dS, \tag{2}$$

where the integral is evaluated over the surface S_0 of the object and $\mathbf{n}$ is the surface normal vector pointing outward the object surface.
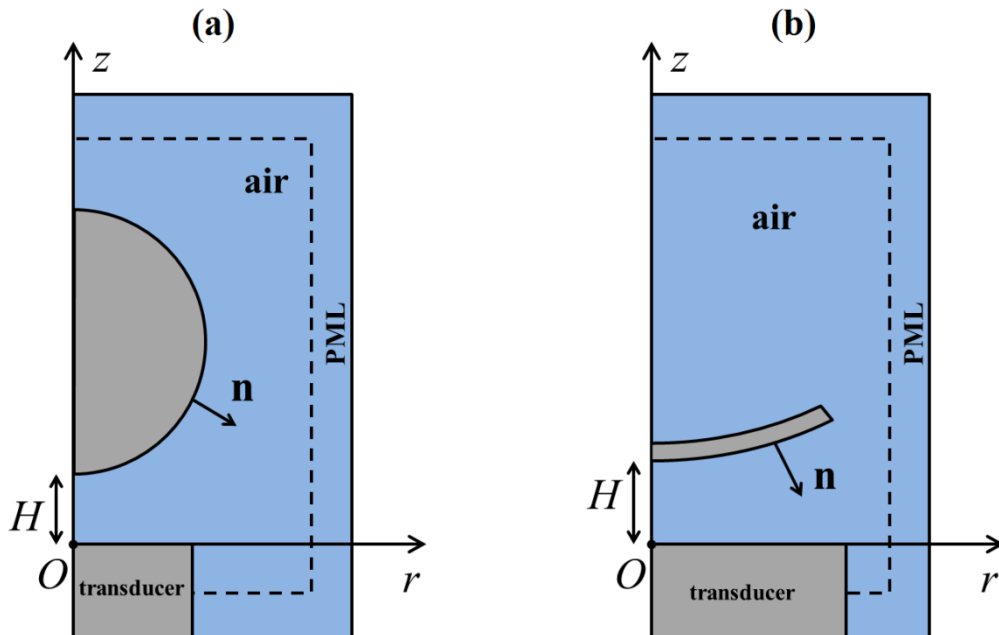

Figure 2: Axisymmetric numerical models used to calculate the axial force on the levitated object: (a) Levitation of a sphere; (b) Levitation of a slightly curved object.

Two axisymmetric models were implemented. The first model, shown in Fig 2(a), is used to calculate the axial acoustic radiation force that acts on a rigid sphere of 50-mm-diameter due to the

ultrasonic wave emitted by a 20-mm-diameter ultrasonic transducer operating at 25.23 kHz. The second model is illustrated in Fig. 2(b) and it is used to obtain the axial force on a slightly curved object located above a 50-mm-diameter transducer operating at 24.57 kHz. In the second model, the integral of Eq. (2) is evaluated at the bottom surface of the object. The slightly curved object has a diameter of 43 mm and its bottom convex surface has a curvature radius of 94 mm. Both axisymmetric models are used to obtain the axial force as a function of H, which is the distance between the transducer surface and the bottom part of the object.

The axisymmetric models illustrated in Fig. 2 can only simulate the axial force on the object. However, a successfully levitation requires also a lateral restoring force. Due to the circular symmetry, the radial force is zero for an object aligned with the transducer main axis. In order to simulate the lateral force that acts on the object, a three-dimensional model is used to obtain the horizontal force as a function of lateral displacement Δx of the object. The three-dimensional model is illustrated in Fig. 3. This model is similar to that presented in Fig. 2(b), but allows obtaining the force $\mathbf{F_{rad}}$ as a function of H and Δx. Due to symmetry, only one half of the model was simulated and symmetric boundary conditions were applied in the xz-plane. Perfectly matched layers (PML) (not shown in Fig. 3) were also employed to avoid wave reflections at the edges of the air domain.
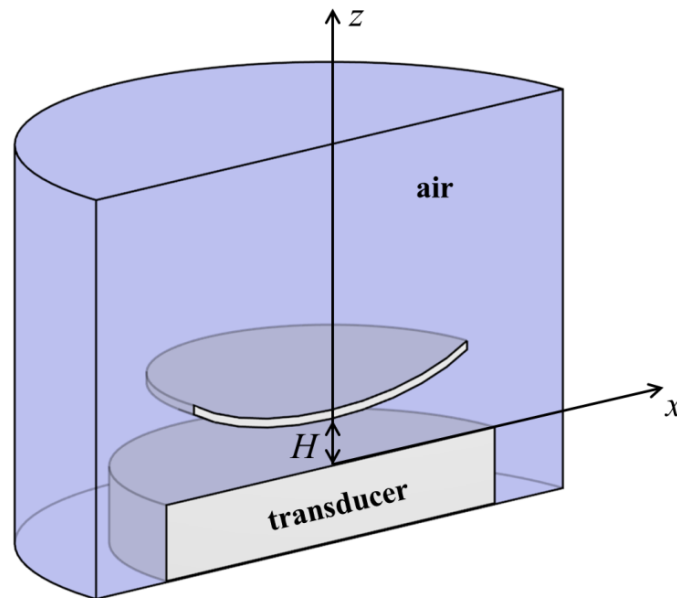

Figure 3: Three-dimensional numerical model used to calculate the lateral force on the levitated object.

4.   Experiments

The acoustic radiation force that acts on a 50-mm-diameter expanded polystyrene sphere was measured by an electronic scale. The sphere was placed on the scale and a Langevin-type transducer attached to a motorized linear stage was positioned above the sphere. The scale and the linear stage were controlled by a code written in Matlab (MathWorks, Natick, MA). With this setup, it was measured the acoustic radiation force on the sphere as a function of H for the transducer operating at 25.23 kHz with its front face vibrating with a displacement amplitude of 15 μm. The details of the experimental setup were described previously [16].

In addition, three custom made 25 kHz Langevin-type transducers arranged in a tripod configuration were used to levitate an expanded polystyrene sphere of 50 mm in diameter and mass of 1.46 g. The transducers were driven by two functions generators (one single-channel and one dual channel) connected to three power amplifiers.

In a second experiment, a custom made Langevin transducer with a plane radiating face of 50 mm in diameter was used to levitate a circular slightly curved object in air. The object was made

of expanded polystyrene, with a diameter of 43 mm and a curvature radius of 94 mm. The transducer was excited with a sinusoidal signal with a frequency of 24.57 kHz.

5. Results

The acoustic pressure distribution p around the sphere obtained with the numerical model of Fig. 2(a) is shown in Fig. 4(a). The numerical model was also used to obtain the particle velocity distribution $\mathbf{u}$. The pressure and velocity distributions were replaced in Eq. (1) to calculate the acoustic radiation pressure, which was replaced in Eq. (2) to obtain the axial acoustic radiation force on the sphere. The ratio between the axial radiation force F_z and the square of the transducer velocity amplitude u_0^2 is presented in Fig. 4(b). Figure 4(b) also shows the ratio between F_z and u_0^2 obtained experimentally. As it can be observed in Fig. 4(b), there is a good agreement between the numerical and experimental curves. The peak occurring at $H \approx 7$ mm is due to the standing wave formed between the sphere and the transducer, as it can observed in Fig. 4(a).
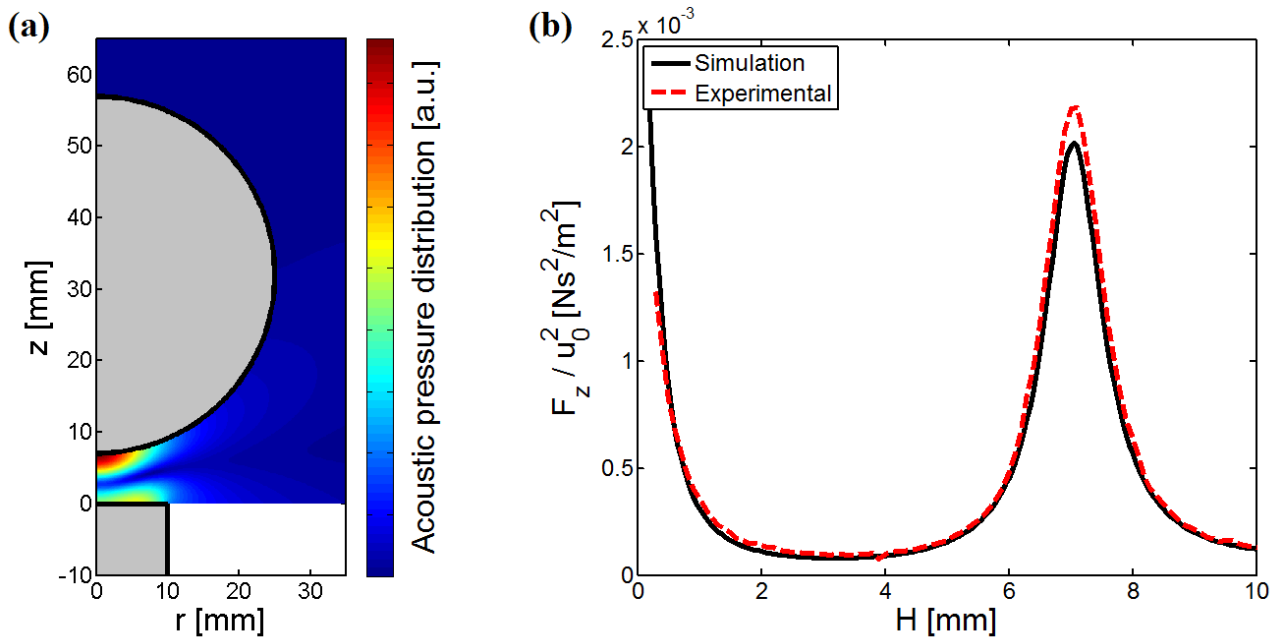

Figure 4: Numerical results obtained with the axisymmetric model of Fig. 2(a) for a transducer radius of 10 mm operating at 25.23 kHz with a velocity amplitude u_0: (a) Acoustic pressure distribution around the sphere for $H = 7.05$ mm; (b) Ratio between the axial acoustic radiation force F_z and the square of the transducer amplitude velocity u_0 on a 50-mm-diameter sphere as a function of H.

The acoustic levitation of a slightly curved object in air was simulated by using the models of Figs. 2(b) and 3. The axisymmetric model of Fig. 2(b) was used to obtain the axial acoustic radiation force on the object, while the three-dimensional model was used to calculate the lateral force when the object is displaced laterally. Figure 5 shows the acoustic pressure distribution between the curved object and the 50-mm-diameter transducer. The results of Fig. 5 were obtained for the transducer operating at a frequency of 24.57 kHz and a levitation height H of 7.6 mm. In Fig. 5(a), the curved object main axis coincides with the z-axis and in Fig. 5(b), the object is horizontally displaced by $\Delta x = 3$ mm. As it can be observed in Fig. 5(a), the pressure distribution is symmetric in respect to the object main axis, and consequently, the horizontal radiation force is zero for $\Delta x = 0$. In Fig. 5(b), the acoustic pressure amplitude is higher on the left side of the object, which produces a horizontal restoring force pointing to the right. This force causes the object to return to its equilibrium position.
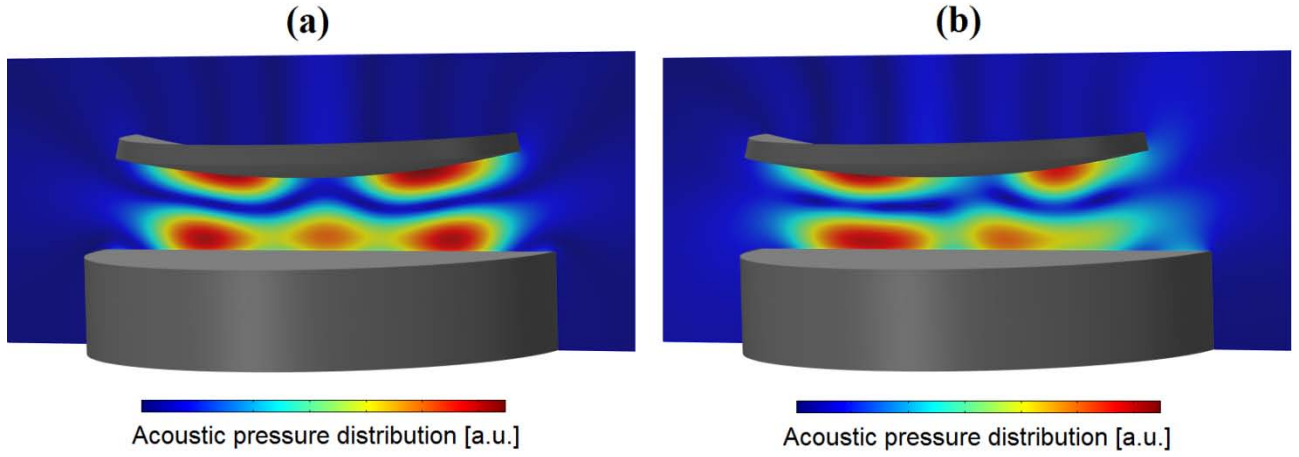
Figure 5: Acoustic pressure distribution around the slightly curved object obtained with the three-dimensional model of Fig. 3: (a) Simulated acoustic pressure for $H = 7.6$ mm and $\Delta x = 0$; (b) Simulated acoustic pressure for $H = 7.6$ mm and $\Delta x = 3$ mm.

The axial acoustic radiation force that acts on the curved object, obtained with the model of Fig. 2(b), is shown in Fig. 6(a). This axial force has a peak at $H \approx 6$ mm and the axial stability is achieved at levitation heights corresponding to the descending parts of the curve. However, a successfully levitation requires not only an axial stability but also a horizontal restoring force to prevent the object of falling laterally. The lateral acoustic radiation force that acts on the curved object as a function of the lateral displacement Δx is presented in Fig. 6(b). This figure presents the lateral force for three different levitation heights ($H = 6.4$ mm, $H = 7.0$ mm and $H = 7.6$ mm). A lateral equilibrium is obtained when the curve presents a negative slope for $\Delta x = 0$. This means that from the three curves presented in Fig. 6(b), only the levitation heights $H = 6.4$ mm and $H = 7.6$ mm can be used for levitation.
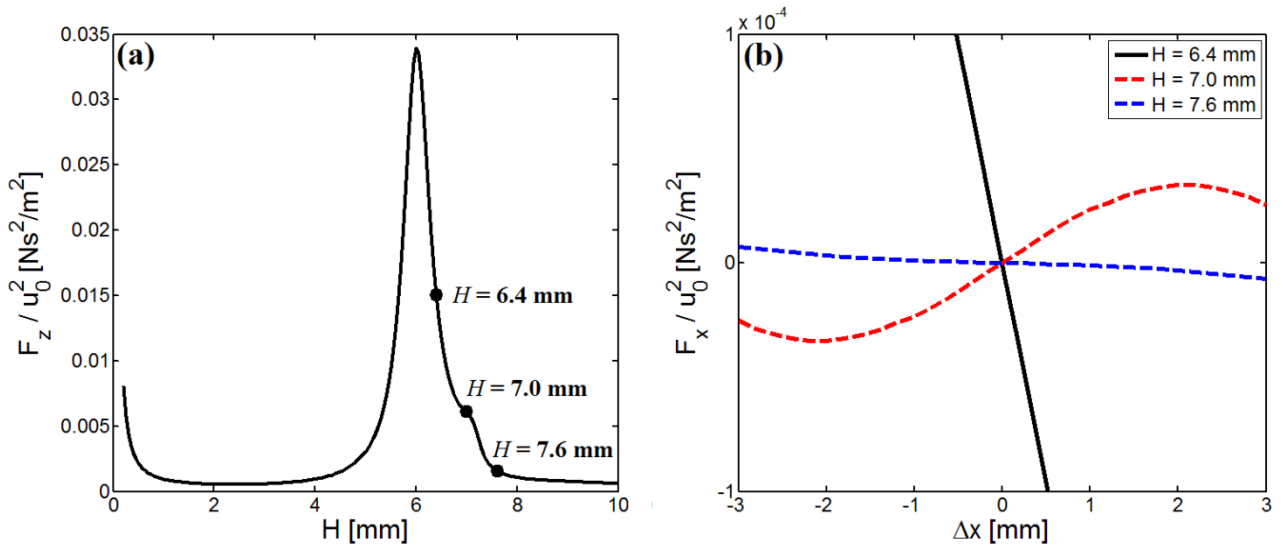

Figure 6: Simulated acoustic radiation force on the slightly curved object for the transducer operating at 24.57 kHz with velocity amplitude u_0: (a) Axial acoustic radiation force simulated with the model of Fig. 2(b); (b) Lateral acoustic radiation force as a function of the lateral displacement of the object for different values of H.

The experimental demonstration of the acoustic levitation of objects larger than the acoustic wavelength is illustrated in Fig. 7. Figure 7(a) shows an expanded polystyrene sphere with a diameter of 50 mm being levitated by three ultrasonic transducers operating at a frequency of approximately 25 kHz. As described previously [14], the vertical and horizontal levitation stability is

achieved by employing three ultrasonic transducers in a tripod configuration. From the experiments, it was observed that a single transducer was only capable of providing an axial force to the object and three transducers were required to achieve vertical and horizontal stability.

Differently from the previous experiment where three transducers were required to levitate a large sphere, a single transducer of 50 mm diameter operating at 24.57 kHz was capable of levitating a slightly curved object weighting 188 mg. The acoustic levitation of the curved object by a single transducer is shown in Fig. 7(b). In this figure, the object is suspended in air a height of approximately 7.6 mm from the transducer surface. At this levitation height, the acoustic radiation force provided an axial force to counteract gravity and a lateral restoring force to prevent the object of falling laterally. It was also observed in the experiments that the levitation height can be slightly altered by changing the transducer velocity amplitude. However, there are some levitation heights in which the curve of Fig. 6(b) presents a positive slope for $\Delta x = 0$. In these cases, we have unstable equilibrium states and the horizontal acoustic radiation force is unable to provide a lateral restoring force to the object.

In the levitation experiments of Fig. 7, it was possible to suspend the objects in air for few minutes. In principle, the objects could be levitated for longer times, but the experiment was stopped after few minutes in order to avoid transducer overheating. As a future work, the numerical models presented in this paper should be applied to optimize the acoustic levitation of large objects in air.
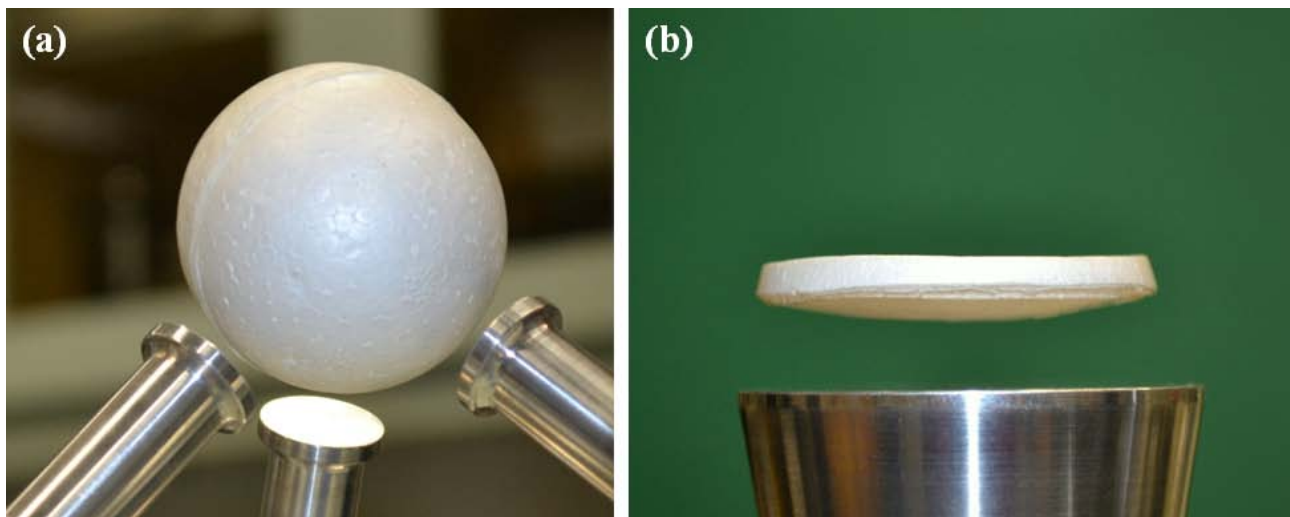

Figure 7: Acoustic levitation of objects larger than the acoustic wavelength in air: (a) Levitation of an expanded polystyrene sphere of 50 mm in diameter by three ultrasonic transducers of 25 kHz; (b) Levitation of a slightly curved object by a single transducer operating at 24.57 kHz.

6. Conclusions

Two strategies to levitate objects larger than the acoustic wavelength were presented together with their theoretical explanation. In the first strategy, three transducers arranged in a tripod configuration were used to provide both axial and lateral levitation stability to a large sphere. In the second strategy, a 50-mm-diameter transducer operating at 24.57 kHz was used to levitate an object having a slightly convex surface in air. The standing wave generated between the transducer and the levitated object was capable of providing both axial and lateral stability. In addition, axisymmetric and three-dimensional numerical models were employed to calculate the acoustic radiation force that acts on the levitated objects. The axial acoustic radiation force that acts on the large sphere was also measured by an electronic scale, showing good agreement with the numerical results. We believe that the levitation strategies presented in this paper can be extended to other large objects having different shapes and size.

7.   Acknowledgements

REFERENCES

1   Démoré, C. E. M., Dahl, P. M., Yang, Z., Gynne-Jones, P., Melzer, A., Cochran, S., MacDonald, M. P. and Spalding, G. C. Acoustic Tractor Beam, *Physical Review Letters*, **112** (17), 174302, (2014).

2   Bruus, H. Acoustofluidics 7: The Acoustic Radiation Force on Small Particles, *Lab on a Chip*, **12** (6), 1014–1021, (2012).

3   Brandt, E. H. Suspended by Sound, *Nature*, **413** (6855), 474–475, (2001).

4   Foresti, D., Nabavi, M., Klingauf, M., Ferrari, A. And Poulikakos, D. Acoustophoretic Contactless Transport and Handling of Matter in Air, *Proceedings of the National Academy of Sciences of the United States of America*, **110** (31), 12549-12554, (2013).

5   Koyama, D. and Nakamura, K. Noncontact Ultrasonic Transportation of Small Objects Over Long Distances in Air Using a Bending Vibrator and a Reflector, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **57** (5), 1152-1159, (2010).

6   Xie, W. J., Cao, C. D., Lü, Y. J. and Wei, B. Levitation of Iridium and Liquid Mercury by Ultrasound, *Physical Review Letters*, **89** (10), 104304, (2002).

7   Andrade, M. A. B., Buiochi, F. and Adamowski, J. C. Finite Element Analysis and Optimization of a Single-Axis Acoustic Levitator, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **57** (2), 469-479, (2010).

8   Ueha, S., Hashimoto, Y. and Koike, Y. Non-Contact Transportation Using Near-Field Acoustic Levitation, *Ultrasonics*, **38** (1), 26-32, (2000).

9   Li, J., Cao, W., Liu, P. and Ding, H. Influence of Gas Inertia and Edge Effect on Squeeze Film in Near Field Acoustic Levitation, *Applied Physics Letters*, **96** (24), 243507, (2010).

10 Marzo, A., Seah, S. A., Drinkwater, B. W., Sahoo, D. R., Long, B. and Subramanian, S. Holographic Acoustic Elements for Manipulation of Levitated Objects, *Nature Communications*, **6**, 8661, (2015).

11 Memoli, G., Caleap, M., Asakawa, M., Sahoo, D. R., Drinkwater, B. W. and Subramanian, S. Metamaterial Bricks and Quantization of Meta-Surfaces, *Nature Communications*, **8**, 14608, (2017).

12 Yarin, A. L., Pfaffenlehner, M. and Tropea C. On the Acoustic Levitation of Droplets, *Journal of Fluid Mechanics*, **356**, 65-91, (1998).

13 Zhao, S. and Wallaschek J. A Standing Wave Acoustic Levitation System for Large Planar Objects, *Archive of Applied Mechanics*, **81** (2), 123-139, (2011).

14 Andrade, M. A. B., Bernassau, A. L and Adamowski, J. C. Acoustic Levitation of a Large Solid Sphere, *Applied Physics Letters*, **109** (4), 044101, (2016).

15 Hong, Z. Y., Zhai, W., Yan, N. And Wei, B. Measurement and Simulation of Acoustic Radiation Force on a Planar Reflector, *Journal of the Acoustical Society of America*, **135** (5), 2553-2558, (2014).

16 Andrade, M. A. B., Ramos, T. S., Okina, F. T. A. and Adamowski, J. C. Nonlinear Characterization of a Single-Axis Acoustic Levitator, *Review of Scientific Instruments*, **85** (4), 045125, (2014).