http://dx.doi.org/10.7567/JJAP.52.100201

Behavior of Ultrasonically Levitated Object above Reflector Hole

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Received April 30, 2013; accepted July 25, 2013; published online September 9, 2013

Using an axis-symmetric model comprising a flat reflector with a hole and a piston vibrator, we simulate the radiation force acting on a small object levitated near the hole, and predict that the position of the object shifts from the center line of the hole. We also experimentally investigate the behavior of a levitated polystyrene sphere approaching the hole. As predicted, the sphere avoids approaching the hole with some distance, depending on the reflector/vibrator interval and the hole diameter. We believe that this effect is useful in discriminating the droplets to be dispensed from those that should not be dispensed.

In recent years, considerable attention has been paid to the noncontact transport of small objects and droplets as an important technology in pharmaceutical industries, and new material science/engineering. Compared with various methods exploiting air pressure[1)] and magnetic/electric fields,[2,3)] ultrasonic-levitation-based methods have a number of advantages such as cost-efficiency, noiseless operation, and applicability to nonelectric/magnetic objects.[4,5)] We have been aiming at implementing all the procedures of the noncontact transport of objects in air using ultrasonic waves, which consist of injection, linear, and circular transport, direction switching, physical/chemical analysis, and ejection. When the objects to be transported are droplets, mixing and dispensing are also included in the procedures. As well as the linear transport,[6)] circular transport and direction switching,[7)] ejection, and droplet mixing, droplet dispensing has also been demonstrated so far.[8)] Other research groups have also reported the properties of ultrasonically levitated droplets,[9,10)] but they aimed at chemical analysis rather than noncontact transportation.

In our previous dispensing experiment,[8)] we showed that by employing a half-cylindrical (not flat) reflector and a step horn driven with a bolt-clamped Langevin transducer (BLT), a single droplet, levitated above a hole of the reflector by adjusting the reflector/horn interval, can fall through the hole into a well with no influence of the residual acoustic field when the vibration is stopped. To achieve our next objective, i.e., the dispensing of a droplet that has been ultrasonically transported for some distance, the acoustic field distribution above the hole needs to be analyzed in detail. Without the hole, the cross section of the experimental setup can be directly used as a model for the finite-element analysis (FEA). However, with the hole, three-dimensional analysis is required, which is practically difficult because of its large amount of calculation.

In this study, by analyzing the acoustic field distribution above a hole using an axis-symmetric model composed of a flat reflector and a piston vibrator, we predict that a levitated object avoids approaching the center line of the hole according to the interval between the reflector and the vibrator. Next, to experimentally observe this phenomenon, we investigate the behavior of a levitated object (polystyrene sphere) when it approaches the hole. The object is levitated below the vibrator, the position of which is fixed, and the position of the reflector is changed. The object predictably avoids approaching the hole with some distance, which depends on the interval between the reflector and the vibrator as well as the hole diameter. This phenomenon is potentially applicable for discriminating the droplets to be dispensed from those that should not be dispensed.

In the noncontact ultrasonic levitation, objects are trapped at the nodal points of the pressure field generated in air between a vibrator and a reflector. The objects are levitated by the acoustic radiation force F_r, which is calculated as[11)]

$$F_r = V\{D\nabla\langle e_k\rangle - (1-\gamma)\nabla\langle e_p\rangle\}, \quad (1)$$

where V is the volume of the levitated object, γ is the ratio of the compressibility of the object to that of the air, and D is given by

$$D = \frac{3(\rho_s - \rho_0)}{2\rho_s + \rho_0}, \quad (2)$$

where ρ_s and ρ_0 represent the densities of the object and the air, respectively. $\langle e_p\rangle$ and $\langle e_k\rangle$ are the temporally averaged potential and kinetic energies, respectively, which are expressed as[11)]

$$\langle e_p\rangle = \frac{|p|^2/2}{2\rho_0 c^2}, \quad (3)$$

$$\langle e_k\rangle = \frac{\rho_0|\nabla\varphi|^2/2}{2}, \quad (4)$$

where p is the acoustic pressure and φ is the velocity potential given by

$$p = \rho_0\frac{\partial\varphi}{\partial t}. \quad (5)$$

Thus, the distribution of the acoustic radiation force can be calculated using the temporally averaged acoustic pressure distribution. Although the theory above is derived under the assumption of $k\cdot a \ll 1$ (k, wave number; a, object radius),[11)] we used this theory in the simulation below for an object with $k\cdot a = 0.5$, expecting moderate analytical errors.

We simulated the acoustic field distribution above a hole employing an axis-symmetric model composed of a 1-mm-thick flat reflector, an end surface of a piston vibrator with 30 mm diameter, and air media between the reflector and the vibrator, as shown in Fig. 1. A sinusoidal vibration at 27.4 kHz (corresponding to the acoustic wavelength of 12.4 mm in air; note that this value is valid only for free space and that the resonance wavelength was 12.9 mm in this model without a hole) with the zero-to-peak velocity of 0.75 m/s

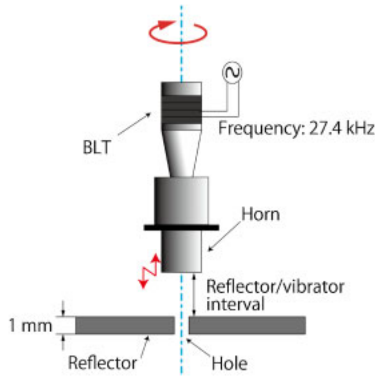


Fig. 1. (Color online) Axis-symmetric model used in the simulation.

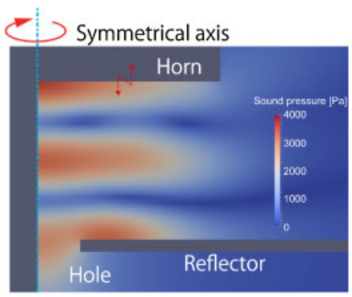


Fig. 2. (Color online) Acoustic pressure distribution calculated by FEA.

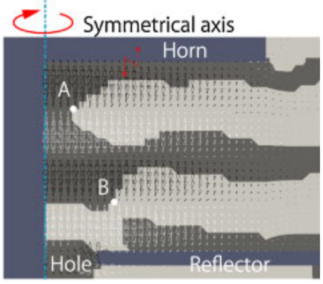


Fig. 3. (Color online) Calculated distribution of the acoustic radiation force.

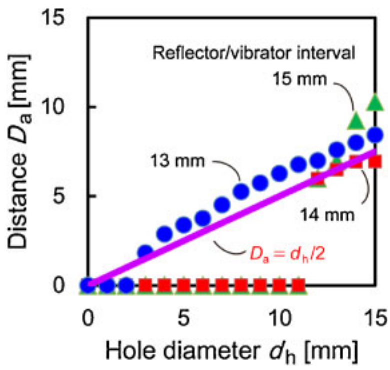
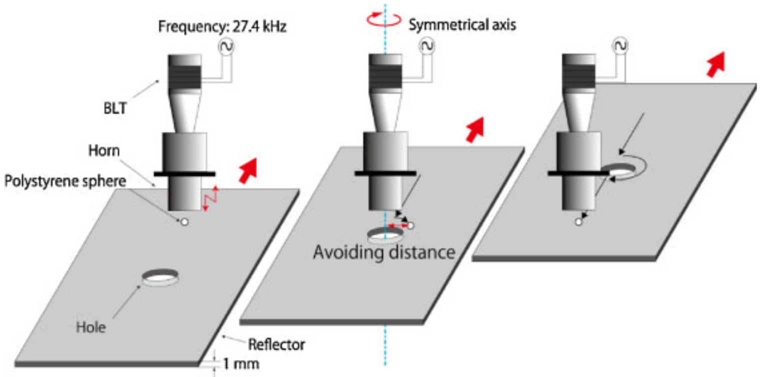


Fig. 4. (Color online) Calculated dependence of the avoiding distance on the hole diameter. The interval between the reflector and the vibrator was 13, 14, and 15 mm.

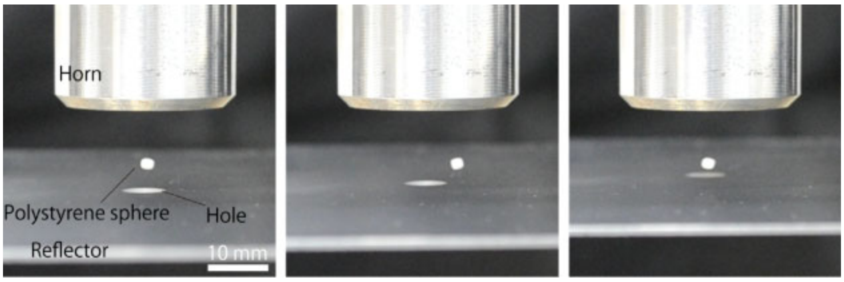
was applied to the end surface of the vibrator. An absorbing boundary condition was used to terminate the air media in the FEA. Figure 2 shows the calculated acoustic field distribution when the hole diameter was set to 7.0 mm and the reflector/vibrator interval was set to 13 mm, where the red and blue regions indicate the areas with high and low temporally averaged acoustic pressures (absolute values), respectively. Then, the distribution of the acoustic radiation force was calculated using Eqs. (1)–(5), as shown as vectors in Fig. 3. In this calculation, each parameter was assumed to be:[12] V, 4.2×10^{-9} m^3, γ, 3.8×10^{-5}, ρ_s, 1.1×10^3 kg/m^3, ρ_0, 1.2 kg/m^3, and c, 340 m/s. The vectors converged on the two nodal lines where an object is levitated. The vectors are almost parallel to the symmetrical axis, but with small components perpendicular to it. The two areas in air indicate the regions where the force acts in the directions away from and toward the symmetrical axis. Therefore, the object is trapped at the boundaries between the two regions in the nodal lines, A and B; here, we defined the distance from the symmetrical axis to the trapping point as the avoiding distance. Figure 4 shows the avoiding distance dependence on the hole diameter for the reflector/vibrator intervals of 13, 14, and 15 mm (in the lower nodal line; B in Fig. 3). With a 13 mm interval, the avoiding distance was calculated to be larger than the hole radius, when the diameter was >3 mm. With 14 and 15 mm intervals, the distance was expected to be larger than the hole radius when the diameter was >12 mm. These simulation results indicate that the trajectories of the levitated objects can be moderately controlled (above the hole for dispensing, or not) by adjusting the reflector/vibrator interval and the hole diameter.

Next, we experimentally observed this phenomenon using the experimental setup depicted in Fig. 5(a). A polystyrene sphere with 2 mm diameter and 3 µg weight was levitated at the lower nodal line between an aluminum reflector and the head of a step horn, and was moved close to a hole of the reflector at the speed of 20 mm/s. The driving frequency of the BLT was 27.4 kHz, and the current and voltage were adjusted so that the end of the horn vibrates at the zero-to-peak velocity of 0.75 m/s. As shown in Fig. 5(b), when the reflector/vibrator interval was 13 mm and the hole diameter was 7 mm, the sphere avoided approaching the hole. Figure 6 shows the measured avoiding distance dependence on the hole diameter for the reflector/vibrator intervals of 13, 14, and 15 mm. Irrespective of the hole diameter, the avoiding distance was larger than the hole radius with a 13 mm interval, but the distance was almost equal to or shorter than the hole radius with 14 and 15 mm intervals. When the hole diameter was larger than ∼10 mm, with 14 and 15 mm intervals, the sphere was not levitated owing to the weak acoustic radiation force (note that when the interval was 12 or 16 mm, the sphere was not stably levitated even without a hole). These measurement results basically agree with the trends that we predicted through the FEA simulation. The discrepancy in the avoiding distance between experiment and simulation seems to be caused by the acoustic field distribution disturbed by the sphere itself[13] along with the value of $k \cdot a$, which is not sufficiently small compared with 1.[11]

In conclusion, first, we analyzed the acoustic field distribution above a hole using an axis-symmetric model



(a)



(b)

Fig. 5. (Color online) (a) Schematic setup and procedure of the experiment. (b) Photographs of the levitated polystyrene sphere avoiding approaching the hole.

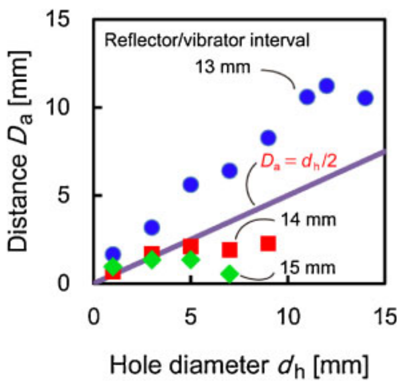


Fig. 6. (Color online) Measured dependence of the avoiding distance on the hole diameter. The interval between the reflector and the vibrator was 13, 14, and 15 mm.

composed of a flat reflector and a BLT-based vibrator. Then, we predicted that a levitated object avoids approaching the hole depending on the reflector/vibrator interval. We also experimentally investigated the behavior of a levitated polystyrene sphere when it was moved close to the hole. The sphere avoided approaching the hole with a certain avoiding distance, which depends on the reflector/vibrator interval and the hole diameter. We believe that this phenomenon can be exploited in developing noncontact ultrasonic dispensing systems in the near future by adding a new function of discriminating the droplets to be dispensed from those that should not be dispensed. The influence of the acoustic field generated with this technique on the phenomena such as deformation, evaporation, and cavitation of the droplets also needs to be studied further.

Acknowledgements The authors are grateful to Mr. Ryohei Nakamura and Mr. Neisei Hayashi, Tokyo Institute of Technology, Japan, for their helpful discussions and comments. This work was partially supported by a Grant-in-Aid for Scientific Research (Challenging Exploratory Research, 23656163) from the Japan Society for the Promotion of Science (JSPS).

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