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Acoustic method for levitation of small living animals

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Ultrasonic levitation of some small living animals such as ant, ladybug, and young fish has been achieved with a single-axis acoustic levitator. The vitality of ant and ladybug is not evidently influenced during the acoustic levitation, whereas that of the young fish is reduced because of the inadequacy of water supply. Numerical analysis shows that the sound pressures on the ladybug's surface almost reach the incident pressure amplitude p_0 due to sound scattering. It is estimated that 99.98% of the acoustic energy is reflected away from the ladybug. The acoustic radiation pressure p_a on the ladybug's surface is only 1%–3% of p_0, which plays a compression role on the central region and a suction role on the peripheral region.
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The levitation and manipulation of objects without material contact are not only a fascinating phenomenon but also a potential technique to counteract the gravity on the ground. The methods include acoustic levitation, magnetic levitation, electromagnetic levitation, electrostatic levitation, superconducting levitation, and so on.[1–4] The containerless processing techniques based on these levitation methods have been applied to the fields of materials preparation, fluid dynamics, and biochemical analysis.[5–9] In the last few decades, the levitated objects are mainly those without life. A surprising and interesting experiment was carried out by Geim[10] and Berry and Geim,[11] who levitated living frogs and grasshoppers by a magnetic field. In this letter, we report the levitation of some small living beings such as ants, ladybugs, young fishes, and so on, with the radiation force of ultrasound.

The levitation of normal solids and liquids by acoustic radiation force has achieved good stability.[12] An interesting question is: What will happen if living beings are sent into the acoustic levitator? We choose small animals not more than 10 mm in geometry to perform the levitation experiment, considering that the size of object is required to be smaller than half a wavelength in acoustic levitation.[13] These small animals live naturally on the ground, in the air, or in water, as shown in Table I.

The experiment was conducted with a single-axis acoustic levitator, which employs a magnetostrictive transducer with a frequency $f=16.7$ kHz and generates a wavelength $\lambda=20.3$ mm in the air at room temperature. This levitator consists of an emitter ($d_E=25$ mm) and a reflector ($d_R=40$ mm, $R=40$ mm), where d_E is the emitter section diameter, and d_R and R are the reflector section diameter and surface curvature radius, respectively. The interval between the emitter and the reflector H is adjusted to be about 1.5λ to excite the $n=3$ resonant mode of acoustic field, where n is the mode of standing wave. In this mode, there are three possible levitation positions along the symmetrical axis among which the middle one is chosen to levitate the living animals. The details of this facility can be found elsewhere.[14]

After the acoustic levitator is adjusted to a proper state, we utilize a tweezer carefully to introduce the animals into the levitation position. Figure 1 shows the levitation process of an ant, a ladybug, and a young fish in air. Since the longitudinal component of the acoustic radiation force F_z is much larger than the lateral components F_r, these animals are usually levitated with the largest cross section of their bodies perpendicular to the reflector-emitter axis, so as to stabilize their posture. The ant is usually levitated with a posture as if it is "crawling" in the air [Fig. 1(a)]. Sometimes, it struggled to escape from the constraint of acoustic radiation force by rapidly flexing its legs [Fig. 1(b)]. However, it failed because its legs can obtain little counterforce from the air. The posture of the levitated ladybug is similar to that when it stands or crawls on the ground [Fig. 1(c)]. We can also place the ladybug into the levitation position with its back downward and belly upward. In this case, the ladybug can hardly turn its body over by itself. Like the ant, the ladybug attempted to escape from the levitation force too. It spread its wings and tried to "fly" away [Fig. 1(d)]. Unfortunately, this attempt failed, too, because the acoustic radiation force is too strong to break away from, or its wings cannot function so well as in the static air. During the levitation of fish and tadpole, water is added to the levitation region every 1 min by a syringe. Nevertheless, only a very thin layer of water can be reserved surrounding the young fish and tadpole because of the limitation of object size. The young fish is usually levitated in a posture of "side lying" [Fig. 1(e)]. It also failed to escape from the ultrasonic field with an action of "swimming" by swinging its tail [Fig. 1(f)].

After a continuous levitation of more than 30 min, we return the animals to their normal living environment. The ant and the ladybug are still with sufficient vitality, and they

TABLE I. Acoustically levitated small living animals.

Living beings	Size (mm)	Habitat
Ant	~5	Ground
Beetle	~9	Ground
Spider	~5	Ground
Ladybug	~6	Air
Bee	~9	Air
Young fish	~10	Water
Tadpole	~10	Water

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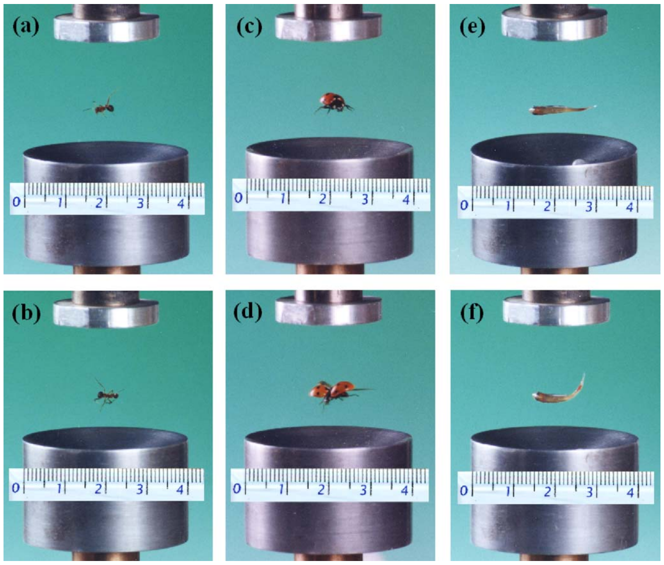

FIG. 1. (Color online) Acoustic levitation of small living animals in air: [(a) and (b)] ant, [(c) and (d)] ladybug, and [(e) and (f)] young fish. The ruler scale in [(a)–(f)] is cm.

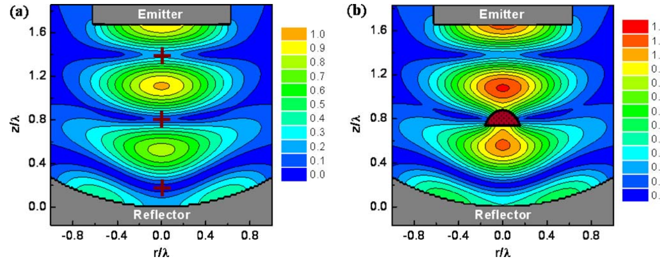

FIG. 2. (Color online) Distribution of the sound pressure field: (a) before the levitation of ladybug and (b) during the levitation of ladybug. The sound pressure at the center of the emitter surface is p_0=3560.8 Pa (SPL =162 dB) before levitation. The coordinates r and z are scaled by the wavelength λ=20.3 mm, and the sound pressure p is scaled by p_0. The cross "+" in (a) indicates the pressure minima which are the possible levitation positions.

can run or fly after the experiment. Mostly because of the inadequacy of water supply, the vitality of the young fish is reduced during the acoustic levitation.

The physical origin of acoustic radiation force comes from the nonlinear effect of high intensity sound or ultrasound. King's theory[13] shows that the substantial time-averaged acoustic radiation pressure p_a results from the second order terms of the sound pressure p and the medium particle velocity $\mathbf{v}$, which can be expressed as

$$p_a = \frac{1}{2}\frac{\rho_0}{c_0^2}\langle p^2\rangle - \frac{1}{2}\rho_0\langle \mathbf{v}^2\rangle, \qquad (1)$$

where ρ_0 and c_0 are the medium density and sound speed, respectively. The anglular brackets in Eq. (1) denote the time average over one period of acoustic oscillation. The integral of the acoustic radiation pressure p_a over the entire surface S of an object makes up of the acoustic radiation force $\mathbf{F}$, which may counteract the gravity and behaves as the levitation force if the object is placed in an appropriate location. Actually, the first term in the right-hand side of Eq. (1) represents a real pressure, whereas the second term is a negative pressure (negative Bernoulli pressure), which results in a suction effect. Consequently, the resultant pressure may be either a positive that plays a compression role or a negative that behaves as a suction force.

To have a brief insight into the physics of the present levitation experiment, a computation is performed for the levitation of a ladybug. The calculation is based on a two-cylinder model of the single-axis acoustic levitator and a partial sphere model of the ladybug. The single-axis acoustic levitator is simplified as two coaxial cylinders: the upper cylinder acts as a vibration source and the lower one as a reflector with a concave surface. The surfaces of the two cylinders are rigid boundaries in the calculation except for the bottom surface of the upper cylinder, which vibrates sinusoidally in the normal direction. The details of this description can be found in a previously published paper.[14] The ladybug is simplified as a partial sphere with 3 mm spherical radius and 2.5 mm height, and its symmetric axis is superposed with the levitator's. Since the ladybug's density ρ_L and sound speed c_L have the same order of magnitude as water ($\rho_L \sim 10^3$ kg/m^3, $c_L \sim 10^3$ m/s), resulting in an acoustic characteristic impedance ($\rho_L c_L \sim 10^6$ kg s/m^2) very larger than that of air ($\rho_0 c_0 \sim 4\times 10^2$ kg s/m^2), the interface between the ladybug (partial sphere) and the air can be also regarded as a rigid boundary in the calculation of the acoustic field outside the ladybug. On the basis of the above simplification, the velocity potential Φ of the acoustic field, which satisfies the Helmholtz equation, can be expressed as the boundary integral equation over the surfaces of the two cylinders and the partial sphere and then numerically solved by boundary element method.

Figure 2 shows the simulated sound pressure field when levitating a ladybug. The incident sound pressure level (SPL) at the emitter center is assumed to be 162 dB (the corresponding sound pressure amplitude is p_0=3560.8 Pa in air), which is the typical SPL for levitating samples having the similar density of water.[15] Before the levitation, the reflector-emitter interval H is adjusted to be H_3=1.69λ to produce the n=3 resonant mode, which has three pressure minima along the symmetric axis and is possible to levitate three samples [Fig. 2(a)]. After the ladybug is introduced into the central region of the levitation space, the reflector-emitter interval reduces to H_3=1.67λ to keep the resonance, because the presence of the ladybug leads to a resonance shift effect.[16] It is clear in Fig. 2 that the introduction of the ladybug arouses an obvious scattering of the incident field, which results in the strengthening of the two pressure maxima near the ladybug by a factor of ~1.2.

The equilibrium position of ladybug is determined by comparing the acoustic radiation force F and the gravity G. The former can be obtained by integrating the acoustic radiation pressure p_a over the ladybug's surface. Because of the axial symmetry of the computation, the direction of F is parallel to the axis. The maximum levitation force reaches 1.5 G. The equilibrium vertical position of the ladybug is z_L=0.79λ, where z_L=0 is located at the reflector surface center.

At the equilibrium position, the sound pressure and the acoustic radiation pressure on the ladybug's surface are further analyzed. Figure 3(a) shows the distribution of the sound pressure amplitude on the ladybug's back and belly. It is clear that the sound pressure at the central region is much larger than that at the rim. Although the ladybug is levitated at the location of pressure node where the incident sound pressure is the minimum, the sound pressure amplitude at the

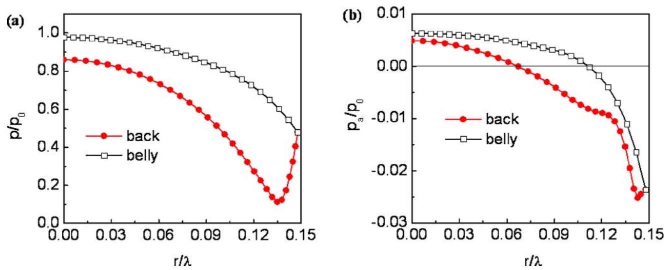

FIG. 3. (Color online) Distribution of (a) sound pressure p and (b) acoustic radiation pressure p_a on the ladybug's back and belly. The reference pressure p_0=3560.8 Pa (SPL=162 dB) is the sound pressure at the emitter center.

back and belly center reaches almost the incident pressure antinode p_0 because of the scattering effect. In order to evaluate the acoustic field inside the ladybug, the compressibility of the ladybug should be taken into consideration. According to the acoustic boundary condition that the sound pressure is continuous at the interface of two media, the sound pressure inside the ladybug is estimated to be the same order of magnitude as on the ladybug's surface, i.e., $\sim 3\times 10^3$ Pa. Assuming that the acoustic characteristic impedance of the ladybug is $\rho_L c_L \sim 10^6$ kg s/m^2, the vibration velocity amplitude inside the ladybug is estimated to be $\sim 3\times 10^{-3}$ m/s, which corresponds to a very small displacement amplitude of $\sim 3\times 10^{-8}$ m. Since the ladybug's characteristic impedance is 1/5000 of the air, the sound energy inside the ladybug is estimated to be also 1/5000 of the air. This means that 99.98% of the sound energy is reflected away from the ladybug's surface into the air.

Figure 3(b) shows the distribution of the acoustic radiation pressure p_a on the ladybug's surface. There exist both positive pressure and negative pressure on both the back and the belly. The positive pressure on the central region of the back and belly plays a compression role, whereas the positive pressure on the peripheral region behaves as a suction effect. Therefore, the acoustic radiation pressure on the ladybug's surface has a tendency to flatten the ladybug, which is evident in the acoustic levitation of liquid drops.[15,17] It should be noted that the maximum positive pressure is less than 1% of the incident sound pressure p_0 and the maximum negative pressure is less than 3% of p_0. Since p_0 is much smaller than the atmosphere pressure, we speculate that neither the sound pressure nor the acoustic radiation pressure leads to a direct injury to the ladybug. Although the acoustic radiation pressure is negligible as compared with the sound pressure and the atmosphere pressure, it provides the levitation force to counteract the gravity.

It is difficult to calculate the sound scattering if the ant, young fish, or the "flying" ladybug is considered because of their complicated geometry. However, we believe that the change of sound field before and after levitation of these animals is similar to Fig. 2 with sound pressure gradient in both axial and lateral directions, except that the distribution is no longer axial symmetrical. Therefore, excellent levitation stability in both longitudinal and horizontal directions has been achieved since the violent movement of these animals cannot interrupt stable levitation in this special environment. The sound pressure and acoustic radiation pressure on the other animals are also estimated to be the same order of magnitude as the ladybug.

In summary, we have levitated some small living beings such as ant, ladybug, and young fish on the Earth with a single-axis acoustic levitator. The vitality of the ant and ladybug is not evidently influenced during the acoustic levitation, whereas that of the fish is reduced because of the inadequacy of water supply. The physical conditions for the levitation of a ladybug are analyzed based on a partial sphere model. The numerical calculation shows that the presence of the ladybug results in an obvious scattering effect of the incident acoustic field and the sound pressures on the central region of the back and belly almost reach the incident pressure amplitude p_0. It is estimated that 99.98% of the acoustic energy is reflected on the ladybug's surface. The acoustic radiation pressure p_a on the ladybug's surface is only 1%–3% of p_0, which plays a compression role on the central region and a suction role on the peripheral region.

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