Acoustic trapping of particle by a periodically structured stiff plate

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(Received 30 August 2011; accepted 28 November 2011; published online 23 December 2011)

We present a study on the acoustic radiation forces exerted on a cylindrical particle near the surface of a periodically structured brass plate. When resonance of the structured plate occurs, this configuration shows an interesting trapping effect, which essentially arises from the gradient force induced by gradient vortex velocity field near the surface. This artificial structure for providing a geometrically modulated trapping force may be of interest for acoustic manipulation and sorting in various complex mechanical systems. © *2011 American Institute of Physics*. [doi:10.1063/1.3670267]

The acoustic manipulation of particles offers a contactless, controllable and noninvasive tool for application to such tasks as particle sorting, chemical sensing, and micro/nano fabricating.[1–3] The interaction of the incident field with particles, manifested as an exchange of momentum, enables the trapping or pushing of particles.[4] Obtaining a strong trapping or pushing force should enable the design of an incident beam profile. However, the conventional system with standing waves or Gaussian beams, which is usually generated directly by acoustic transducer, cannot be redesigned easily, nor can the corresponding acoustic radiation forces be modulated efficiently.[1,5] Thus, it is worthwhile to seek a tunable acoustic force using artificial systems.

Since their inception, phononic crystals have been associated mainly with the concept of controlling the propagation and spatial confinement of acoustic waves.[6,7] Indeed, the enhanced spatial confinement of an acoustic wave means that strong variations of wave intensity can be achieved over a small region of space and therefore can exert a large acoustic force on a particle immersed in the confined field. However, except for Cooper's recent works on phononic crystals for shaping and driving microfluids,[8,9] insufficient research has focused on the use of phononic crystal structures (especially a phononic crystal plate) for acoustic trapping.

Recently, He and co-workers demonstrated that a periodically structured stiff plate can generate a vortex field near its surface at its resonant frequency.[10] In this article, we demonstrate the alternative possibility of the acoustic trapping of particles by this system. We studied numerically the acoustic radiation force on a cylindrical brass particle near the surface of a periodically structured brass plate and investigated the capability of acoustic trapping. Here, the calculation supports that the particle is in a nonviscous fluid (in this case water), thermo-viscous effects, and acoustic streaming are neglected. This situation holds in various experimental situations.[11] We demonstrated that this system has trapping wells around the surface between the periodic stubs, which stem from the gradient force induced by the gradient vortex velocity field near the surface. The resonant-induced trapping force is mainly affected by the resonant frequency of the system, which is geometrically dependent on the ratio of the plate thickness to the structural period.[10] Therefore, the trapping force on the particle is tunable and reconfigurable.

As shown in Fig. 1(a), the system under consideration consists of a cylindrical particle with radius R on top of a periodically structured brass plate with a separation distance Δy from the bottom of the particle to the surface of the plate, and a distance Δx from the center of the particle to the central axis perpendicular to the plate. The thin brass plate (thickness t) is patterned with a periodical array (period d, normalized constant) of the square brass gratings (length

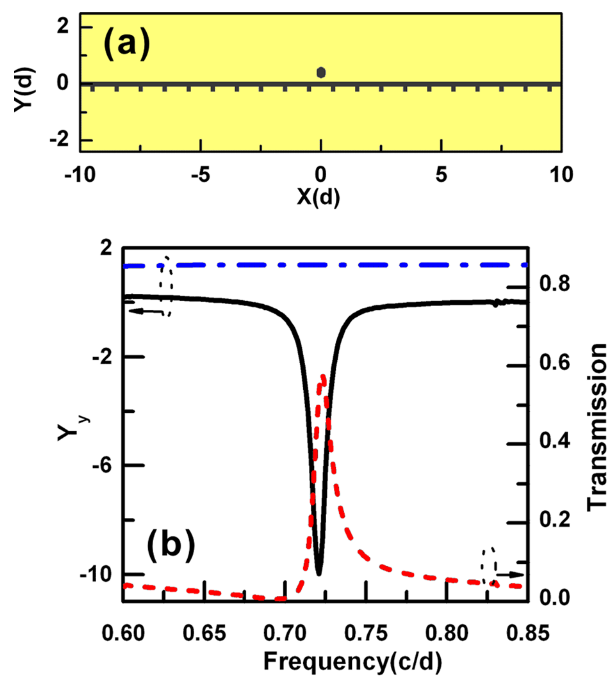

FIG. 1. (Color online) (a) Schematic view of a uniform brass plate with a periodically patterned rectangular brass grating on the downside, a cylindrical particle is placed on the topside of this structured plate. (b) Dimensionless acoustic force function Y_y exerted on the brass particle in (a) versus frequency (dark solid line), and on the brass particle immersed in a pure plane wave versus frequency (blue dot-dash line). The corresponding transmission of the system of (a) versus frequency is shown in short red dash. The plane waves are normally incident from the bottom.

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TABLE I. Elastic constants of materials.

	Density [kg/m^3]	Longitude velocity [m/s]	Transverse velocity [m/s]
Water	1000	1490	0
Brass	8600	4400	2100

side a) on the downside. The particle and structured plate are immersed in water. Unless otherwise specified, these parameters are set at: $R = 0.2d$, $\Delta x = 0$, $\Delta y = 0.09d$, $t = 0.245d$, and $a = 0.21d$. The corresponding normalized frequency is c/d, and c is the sound speed in water. The material parameters in all calculation are given in Table I. The finite-difference time-domain (FDTD) technique is applied to the calculation of the distribution of pressure (stress) and velocity fields in every temporal and spatial grid; standard perfectly matched layers (PMLs) are used at the computational boundaries to provide absorbing boundary conditions in the x and y directions. The FDTD technique is then used to obtain the time-average acoustic force $F_{x(y)}$ on the cylindrical object in x(y)-directional and the incident acoustic wave energy I_0 across the object position as absence of the object. The dimensionless acoustic force function $Y_{x(y)} = F_{x(y)}/I_0$ is used to evaluate the force on the cylindrical particle.[12]

Fig. 1(b) shows the y-directional dimensionless acoustic force function Y_y and corresponding transmission versus frequency. The dark solid line indicates the Y_y on the brass particle in Fig. 1(a); the plane wave is normally incident from the bottom. The x-directional dimensionless acoustic force function Y_x is approximately zero as the field around the particle is symmetric with respect to the x-axis and is not displaced in the figure. The blue dot-dash line shows the corresponding Y_y on the brass cylindrical particle immersed in a pure plane wave without the structured plate. In addition, the short red dashes indicate the power transmission at normal incidence for the structure in Fig. 1(a). It is clearly observed that the frequency of the enhanced acoustic transmission peak coincides well with that of the negative acoustic radiation force dip. At off-resonant frequencies, the forces on the brass particle are positive (along the propagation direction of the plane wave) and smaller than in the case of a pure plane wave. At resonant frequencies, the forces are interestingly negative, directing to the patterned brass plate surface. The maximum force amplitude is about *ten* times larger than that in a pure plane wave.

To understand the mechanism of the negative force on the particle at resonance frequency, we calculate the velocity, pressure fields and the y-directional force elements around the particle at the frequencies of both negative force and positive force. Fig. 2(a) shows the distribution of the velocity fields for the frequency $f = 0.72(c/d)$ in which the force has a maximum negative value. Both the amplitude field (color variations) and the vector field (arrows) are provided. Fig. 2(b) shows the corresponding pressure field in water.

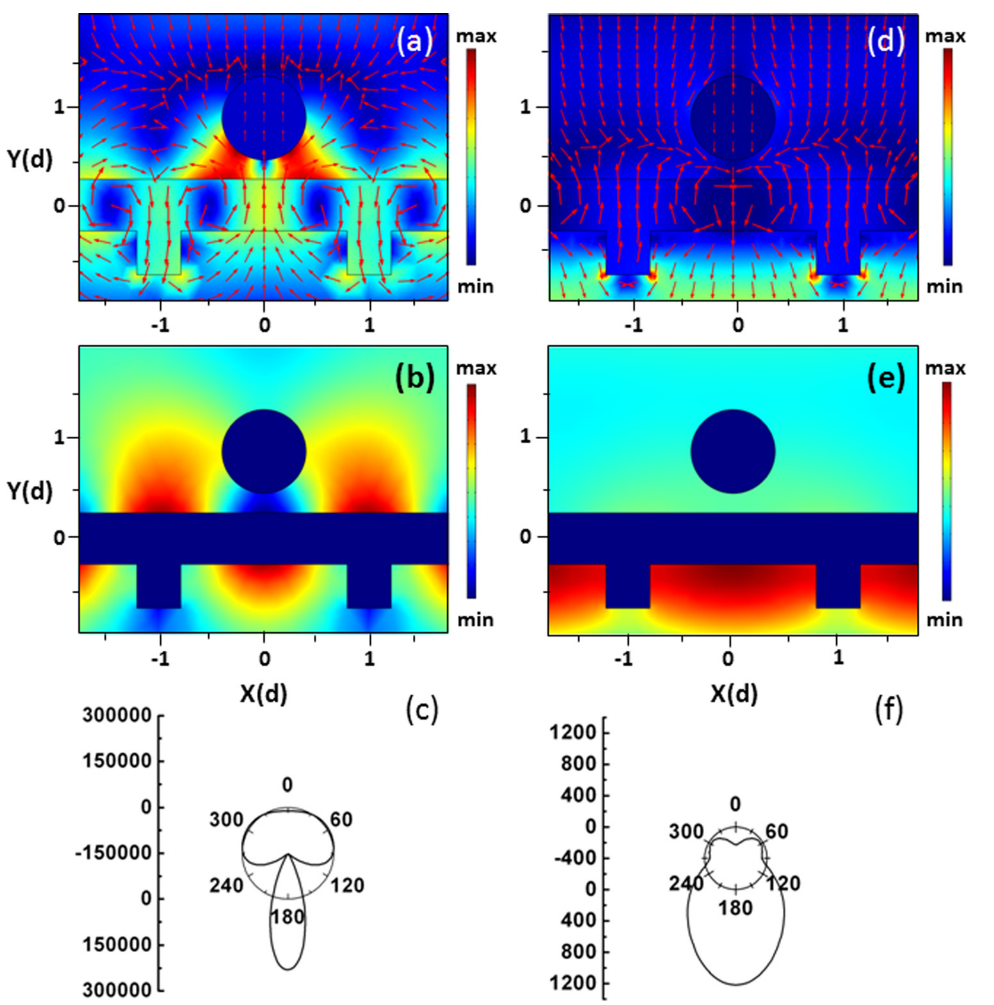

FIG. 2. (Color online) Distribution of the velocity field (a), pressure field in water (b) and y-directional force element around the cylindrical brass particle (c) for the frequency $f = 0.72(c/d)$. The corresponding velocity field (d), pressure field in water (e), and y-directional force element around the cylindrical particle (f) for the frequency $f = 0.64(c/d)$.

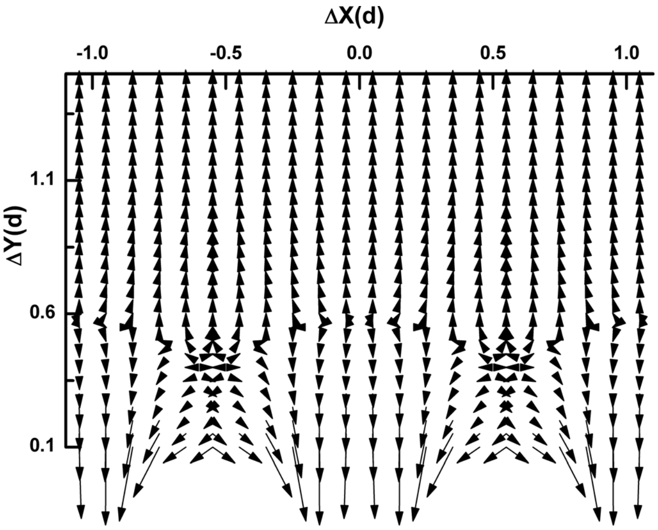

FIG. 3. Total radiation force map exerted on a brass cylindrical particle with $R = 0.2d$ on the flat side of the patterned brass plate for frequency $f = 0.72(c/d)$ with its position Δx from $-1.1d$ to $1.1d$, Δy from $0.1d$ to $1.5d$.

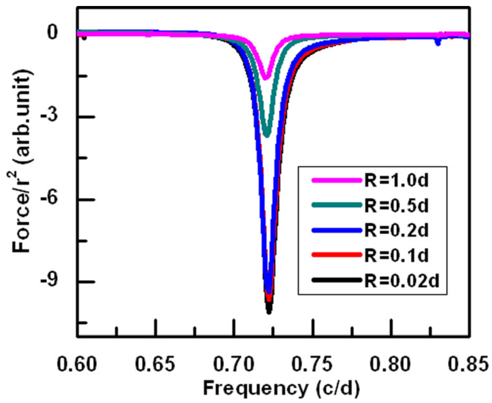

FIG. 4. (Color online) Y-directional acoustic radiation force normalized to the square of radius versus frequency on brass cylindrical particles with different radii.

Since the stress in both the plate and particle is a tensor, the intensity is far larger than the pressure in water, which is not shown in the figure. Fig. 2(c) shows the corresponding time-average y-directional force elements around the particle using a polar graph. The y-directional net force on the particle can be obtained by integrating these force elements. The position of the circle for calculating these force elements is fixed, which is in the water and a litter larger than the radius of the particle. The angular value around the circle indicates the position of the force element: 0° indicates position at the upper side of the cylinder, while 180° indicates the bottom of the particle near the structured brass plate, the radial coordinate indicates the y-directional force element, and the unit is arbitrary. Figs. 2(d), 2(e), and 2(f) show the velocity field, the pressure field in water and the force elements around the particle at the frequency $f = 0.64(c/d)$ in which the y-directional net force on the particle is positive.

As shown in Figs. 2(c) and 2(f), the force elements at the bottom of the particle always have positive values at both resonance and off-resonance frequencies. However, at the resonance frequency, the force elements have negative values around the regions that range from 90° to 170° and from 190° to 270°. Accordingly, as shown in Fig. 2(a), the velocity field at resonance frequency has a gradient distribution in these regions, which make a major contribution to the net negative force on the particle.[13]

To further investigate the trapping effect of this system, Fig. 3 shows the corresponding total radiation force map on the brass particle at the resonance frequency $f = 0.72(c/d)$ with its position Δx from $-1.1d$ to $1.1d$, and Δy from $0.1d$ to $1.5d$. The force direction and intensity are indicated by the direction and length of the arrow. It is clearly shown that the force distributions are symmetric and provide a stable trap for the brass particle with Δy smaller than $0.5d$ while Δx lies between the periodic rectangular brass stubs of $\pm 0.25d$. The nearer the particle is to the surface, the larger the attractive (negative) force. In addition, when Δy is approximately $0.5d$, the acoustic radiation force changes from negative to positive. Consequently, at resonance frequency when the particle is near the surface of the periodically structured brass plate, the corresponding gradient force induced by gradient vortex velocity field near the surface overcomes the scattering force induced by the scattering field, attracting the particle approaching the surface (toward regions of higher intensity). Conversely, at the non-resonant frequencies or when the particle is not near the surface, the gradient force rapidly vanishes. The scattering force is dominant, which is positive and pushes the particle away from the surface.[14]

As shown in Fig. 4, the Y-directional force values normalized to the corresponding square of the radius (i.e., the force densities) versus frequency are investigated, and we evaluate the relative magnitudes of the acoustic radiation forces for cylindrical particles of different sizes. It is noted that when the radius is smaller than $0.2d$, the negative force densities at resonance frequency are relatively large and fixed, while when the radius is larger than $0.2d$, the corresponding negative force densities become smaller as the radius increase. Therefore, the smaller the radius of the particle is, the larger it is exerted acoustic radiation force density. This may be the result of the comparatively constant gradient field distribution and the weak scattering field effect for small particles. It is also demonstrated that this system has a better trapping effect and may counteract the gravity force for smaller particles.

In this paper we have reported on the possibility of using a patterned plate to trap particles. The trapping force on the particles originates from the gradient resonant vortex velocity field near the surface of the patterned brass plate. The resonance frequency of the patterned structure is geometrically dependent on the ratio of the plate thickness to the structural period, and the trapping force on the particle is tunable and reconfigurable. We also performed a detailed analysis of the relationship between the acoustic force and the size of the particle, and justified the equilibrium and stability of the system. In addition, the surface to trap particle in the patterned structure is purely planar; the patterned structure can be easily integrated on a chip by using a conventional micro fabrication process. Further extensions of this work could be investigating real particles with three dimensions as well as experimental demonstration. The geometrically trapping effect for this system on kinds of small particles may have application in various complex mechanical systems.

The work was supported by National Science Foundation (Grant Nos. 10904095, 10904094, 61020106008, 81027006, 61002001, 61031003, and 11002152), National Basic Research Program 973 (Grant Nos. 2011CB707903 and 2010CB534914) from Ministry of Science and Technology, China, and HPC Laboratory, SIAT, CAS, China.

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