A π-Shaped Ultrasonic Actuator for the Noncontact Trapping of Small Particles

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Abstract

A π-shaped ultrasonic actuator is proposed for the noncontact trapping of small particles. In this actuator, two metal plates clamp a multilayer piezoelectric vibrator by a small bolt, and the metal plates are tapered in their lower parts so that a vibration gradient can be obtained. The flexural vibration of the metal plates is used to generate an acoustic field in the gap between the two tapered metal plates. At a driving frequency about 152.8kHz, small particles such as sugar crystal, rice powder, shrimp eggs and grass seeds can be trapped in the gap. It is observed that the particles with an average diameter less than several hundred microns can be trapped stably, without contact with the vibrator. Furthermore, the relationship between the amount of the trapped particles and the input power is investigated under various conditions. The amount of the trapped particles increases as the input power increases. The particles are ejected out of the actuator and therefore cannot be stably trapped if the input power is too large.

1. Introduction

The technology of capturing small particles is useful in the area of biotechnology, micro-machinery and powder process. In this technology, small particles are trapped by the radiation pressure, which results from focused laser beams, ultrasonic beams, and electrostatic force. Ashkin proposed a device that can trap latex spheres of 0.59µm, 1.31µm and 2.68µm by focused laser beam in 1970 [1], and it has already been used to collect biomedical materials such as protein molecules. The weakness of the optical trapping of micron-sized particles is that the particles can hardly be trapped in the optical potential well if the refractive index of the particles is smaller than that of the surrounding fluid, and the reflection and absorption of the particles are not proper. Inspired by Ashkin’s work, particle capture using acoustic radiation pressure was proposed and investigated [2]-[6]. The particles that cannot be handled by laser beams may be manipulated by this technology. Also, it is easier to concentrate small particles by this technology. In these previous studies, high frequency sound field (over 1 MHz) was used to trap or manipulate the small particles.

In this study, a π-shaped ultrasonic actuator that can levitate and trap small particles is proposed. The actuator may generate a standing wave field with a gradient in the gravitational direction in a small gap. Small particles such as the shrimp eggs with an average diameter of 240µm, clusters of rice powder, etc. can be levitated in the gap by the gradient of the sound field, and stably trapped at the nodal points of the sound field.

Fig. 1: Schematic diagram of the ultrasonic actuator. (a) Structure; (b) side view.
2. Construction and principle

Fig. 1 and 2 show the construction of the π-shaped actuator. Two piezoelectric rings are pressed onto two metal plates by a bolt structure. The poling directions of them are shown in Fig. 1(a). The piezoelectric rings have an outer diameter of 12mm, inner diameter of 6mm and thickness of 1.2mm. The two metal plates made of aluminum are tapered in their lower parts, as shown in Fig. 1 (a) & (b). Each plate is 50 mm long and 20mm wide. The thickness of the upper part of each metal plate is 3mm, and the length of the tapered part is 30mm. So the taper angle $\theta$ of the metal plates is about 5.7°.

When the 1st order thickness vibration mode is excited in the upper part of the actuator, the two tapered metal plates do a flexural vibration with a gradient in the height direction [7]. Therefore, a standing wave sound field is generated in the gap between the two plates, which also has a gradient in the height direction. Due to the small thickness of the lower part of the metal plates, the vibration of the lower part of the metal plates is quite strong, and so is the sound field in the lower part of the gap. Small particles with different weights can be trapped at the nodal points of this sound field, without contact with the metal plates.

To verify the contribution of the gradient of the sound field, we investigated the operation of the actuator when the two metal plates have uniform thickness and the other dimensions are identical, as shown in Fig. 3. It was found that the small particles used in our experiments could hardly be levitated in the available vibration range of the actuator. In this case, the vibration of the lower part of the actuator is not large enough, and so is the standing wave sound field in the lower part of the gap.

3. Experimental methods

The operating frequency of the actuator is about 152.8kHz. The particles used in our experiments are shown in Fig. 4, and their densities are shown in Table I. The experimental procedure for trapping particles is shown in Fig. 5. First, the tapered part of the vibrating actuator was inserted into the collection of particles. Then, the actuator was lifted and moved onto a glass slider. Finally, the voltage applied to the actuator was switched off, and the dropped particles on the glass slider were counted by microscope system (Olympus BX-51, Japan). The non-contact trapping of the particles was recorded by digital camera (Canon Power Shot S30, Japan).

![Fig. 2: Photo of the actuator with tapered metal plates.](image)

![Fig 3: Photo of the actuator with uniform metal plates.](image)

Table I: Density of the particles used in the experiments

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (g/cm$^3$)</th>
<th>Approximated Weight per Particle (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brine Shrimp Eggs</td>
<td>0.49</td>
<td>1.86E-05</td>
</tr>
<tr>
<td>Fine Sugar</td>
<td>0.53</td>
<td>3.02E-08</td>
</tr>
<tr>
<td>Grass seeds</td>
<td>0.51</td>
<td>1.90E-03</td>
</tr>
<tr>
<td>Rice powder</td>
<td>0.81</td>
<td>2.48E-07</td>
</tr>
<tr>
<td>Salt</td>
<td>1.37</td>
<td>6.36E-05</td>
</tr>
<tr>
<td>Thyme seeds</td>
<td>0.17</td>
<td>4.00E-04</td>
</tr>
</tbody>
</table>

4. Results and discussion

The non-contact trapping of the brine shrimp eggs and grass seeds is shown in Fig. 6 (a) and (b), respectively. The relationships between the number of trapped particle and the input power were measured for brine shrimp eggs and grass seeds. The result for brine shrimp eggs is
shown in Fig. 7(a), and the one for grass seeds shown in Fig. 7(b). There exists a range of input power in which the number of trapped particles is maximum. When input power is lower than this range, the number of trapped particles increases with increasing the input power. When input power is higher than the range, the number of trapped particles decreases with increasing the input power. Also, it is seen that when the mass of the particle is large, the relationship between the number of levitated particles and the input power is a step function.

These phenomena may be explained as follows. It is known that the particles are trapped at the positions where the time-averaged force potential of the sound field is minimum. In other words, the trapping positions of particles are not continuous. Also, to levitate a particle in the height direction, the local maximum acoustic radiation force in the height direction must be larger than the weight of the particle; so the input power of the actuator must be larger than a critical value. When the input power is low, only the lower part of the sound field in the gap can generate sufficient radiation force to levitate the particles. As the input power increases, the vibration in the upper part of the sound field increases, and this part can also generate large enough radiation force to levitate the particles. So, the number of the trapped particles increases as input power increases, as shown in Fig. 7. While the input power is too large, some of the levitated particles are ejected out of the actuator from the two sides of the gap of the upper part. The larger the vibration, the stronger the ejection is. So when the input power is large enough, the number of the trapped particles decreases as the input power increases.

5. Summary

A novel low frequency ultrasonic actuator for trapping small particles without contact has been proposed, and its ability to trap small particles without contact was verified by experiments. Particles of spherical and irregular shapes can be trapped without contact. In the case of the brine shrimp eggs with a diameter of \(240\mu m\), up to 96 particles can be trapped.

6. References

Fig. 7 Relationships between the number of the trapped particles and the input power of the actuator. (a) Brine shrimp eggs; (b) grass seeds.