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Particle Trapping by W-Shaped Ultrasonic Actuator

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ABSTRACT

This paper reports a method of trapping particles by a W-shaped ultrasonic actuator. The actuator containes two tapered metal strips stacked together, and a transducer used to excite ultrasonic vibration in the metal strips. The two sharp edge of each tapered metal strip in ultrasonic vibration can be used to trap particles such as medicine pills. Analyses of the acoustic radiation force on a particle below the sharp edges shows that the trapping is caused by spatially non-uniform kinetic energy density in the ultrasonic field around the particle. Trapping characteristics of the actuator have been investigated experimentally and theoretically.

INTRODUCTION

Trapping of particles is the base of particle manipulations such as removal of particles from a solid surface, extraction of particular particles from particle mixture, separation of different particles, transport of particles to a desired location, etc. Compared with the optical trapping of particles, acoustic trapping of particles has the following merits. (1) Its trapping capability is not affected by the optical properties such as refractive index and absorption coefficient, which allows the use of one device to trap particles of different optical properties. (2) It can trap particles by radiation surface, which allows a higher stability of trapped particles. (3) It can trap more particles simultaneously.

In this work, we proposed a method of trapping particles by ultrasonic actuator, analysed its operating mechanism, and clarified some trapping characteristics of the method.

CONSTRUCTION AND OPERATING MECHANISM

Structure and size of actuator

The structure of the actuator used to trap particles in our experiment is shown in Fig. 1. In this transducer, two identical metal strips made of Aluminum are stacked and clamped to a Langevin transducer. The upper part of the strips is a rectangular metal plate, and the lower part is a V-shaped metal strip. The upper part has a size of 40 mm × 45 mm × 1.5 mm with a 10 mm diameter hole at its center; the lower part has a length of 99 mm, width of 22.5 mm and thickness of 1.5 mm, tapers off from the upper end to its sharp edge. In this way, a triangular air gap is formed between the two V-shaped metal strips, which has a thickness of 1.5 mm at the lower end. The Langevin transducer has a resonance frequency of 25.3 kHz.

Operating mechanism

A flexural vibration is excited in the Aluminum strips when an AC voltage with a frequency close to the resonance frequency of the ultrasonic actuator is applied. This flexural vibration will generate a sound field, and the sound field near the lower end of gap can generate an acoustic radiation force to suck the particles to the lower end of strips, as anlyzed below.

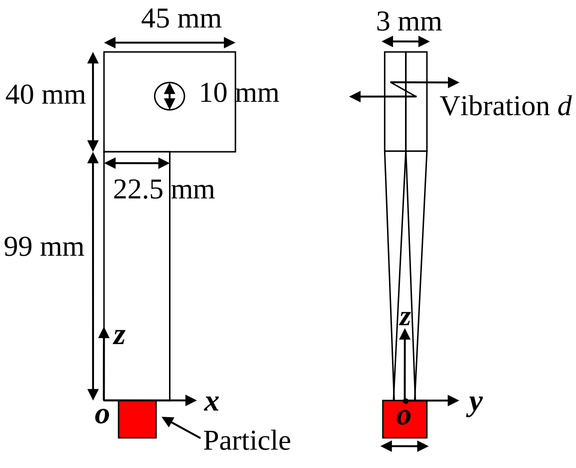


Figure 1. Structure and size of the W-shaped ultrasonic actuator with two V-shaped metal strips**.**

The acoustic radiation force $\boldsymbol{F}$ on a rigid immovable object in a sound field in ideal fluid is given by the following integration over the surface of the object [1-4].

$$\boldsymbol{F} = \left\langle \iint_S (K - U)\boldsymbol{n} dS \right\rangle \qquad (1)$$

where the notation $\langle\rangle$ denotes time average over one period, $\boldsymbol{K}$ is the kinetic energy density, $\boldsymbol{U}$ is the potential energy density, and $\boldsymbol{n}$ is the outward normal unit vector of the surface.

The kinetic and potential energy densities K and U can be calculated by

$$K = \frac{\rho_0 v^2}{2} \quad (2)$$

$$U = \frac{p^2}{2\rho_0 {c_0}^2} \quad (3)$$

where ρ_0 and c_0 are the density of and sound speed in the fluid, v is the velocity, and p is the sound pressure.

Figure 2(a) shows the mesh of the half structure (a single strip, half of a 3 mm × 3 mm × 3 mm cube particle and the surrounding sound field) in 3D FEM calculation of acoustic radiation force on a 3 mm × 3 mm × 3 mm cube particle under the actuator, by the acoustic module of COMSOL Multiphysics. In the calculation, the amplitude of the y-directional vibration displacement (0-peak) of the upper part of metal plates d is 10 μm; the loss factor of the vibration in Aluminum is 0.02; p = 0 is used for the xz-plane; the rest sound field boundaries are the radiation boundary.

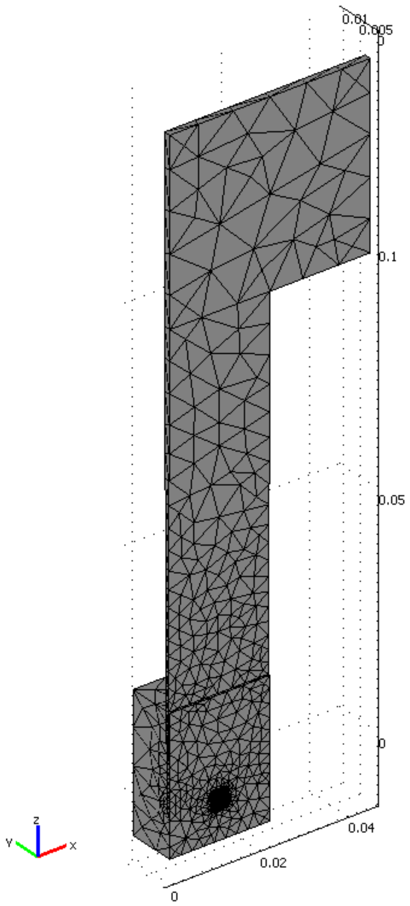
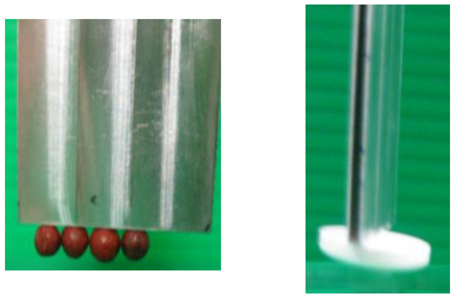


Figure 2. 3D FEM analyses of the half structure in air when vibration displacement amplitude (0-peak) of upper part of metal plate is 10 μm.

From the calculation, it is known that $\iint_S \langle K \rangle dS$ and $\iint_S \langle U \rangle dS$ on the top surface of the cube particle due to the flexural vibration of the metal strips are calculated to be 6.5 × 10^{-4} N and 1.2 × 10^{-5} N, respectively; thus on the top surface $\iint_S \langle K \rangle dS$ is much larger than $\iint_S \langle U \rangle dS$. Also it is found that $\iint_S \langle K \rangle dS$ and $\iint_S \langle U \rangle dS$ on the side and bottom surfaces of the particle are less than 1% of that on the top surface; thus they are negligible. So $\boldsymbol{F}$ has the same direction as $\boldsymbol{n}$ [see Eq. (1)], and the particle may be sucked to the sharp edge of the strips when the sound field is strong enough. Therefore for our actuator, the acoustic radiation force acting on particle is determined by the force on the top surface of particle, pointing upwards.



(a) (b)

Figure.3 Trapping of meci**ne** pills in air by the actuator

Fig. 3 shows the trapping of medicine pills in air by the operating actuator. The particles in Fig. 3(a) (pill A) have a radius of 1.57 mm and density of 1.2 g/cm^3. The particle in Fig. 3(b) (pill F) have a radius of 6.4 mm, thickness of 1.84 mm and density of 1.1 g/cm^3. The mass of pills A and F is 19mg and 256mg, respectively. In the experiment, the vibration displacement (0-peak) at the corner of the sharp edge is 34 μ m.

EXPERIMENTAL AND THEORETICAL RESULTS

In the trapping experiments of this work, the sharp edges of vibrating metal strips of the actuator are inserted into the collection of particles in a container, then the actuator is lifted up.

Fig. 4 shows the experimental relationship between the number of trapped pills A and driving frequency at different input voltages in air. It can be observed that the number of trapped pills reaches a maximum at a particular driving frequency or in a particular driving frequency range for a given voltage, which is caused by the resonance of the transducer system.

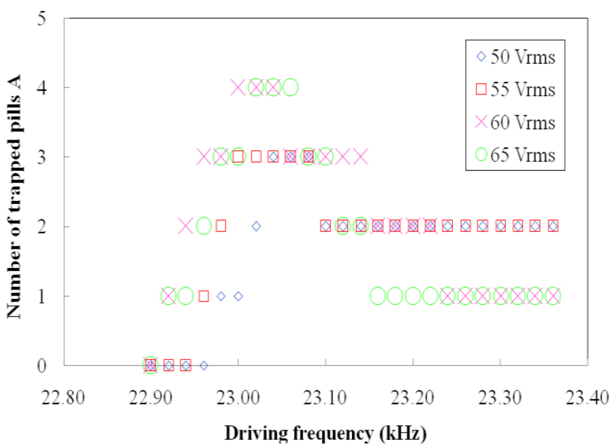


Figure 4. Experimental relationship between the number of trapped pills A and the driving frequency in air under different input voltages.

Figure 5 shows the calculated relationship between the normalized trapping force acting on pill A and the length of V-shaped metal strip when the gap thickness is 1.5 mm. In the calculation, 2D FEM and Gorkov's theory is combined to calculate the acoustic radition force. It is seen that the normalized trapping force reaches its peak when the strip length is 99.1 mm long, which means the trapping capability is the best in the calculated range of strip length. The number of trapped pills A is measured, when the actuators with a constant gap thickness of 1.5 mm and different strip lengths, operates at an input voltage from 50 V_{rms} to 65 V_{rms} at resonance. The results are shown in the Fig. 6. It is seen that the trapping capability is the best at the strip length of 99 mm; no particles can be sucked when the strip lengths are 97 mm and 100.5 mm. Comparing Figs. 5 and 6, it is known that experimental result agrees well with the calculated one.

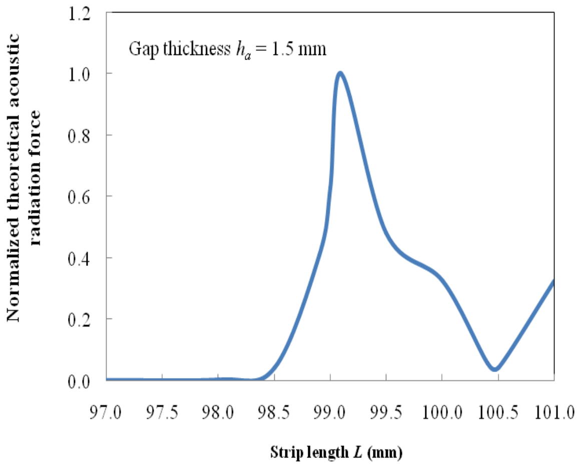


Figure 5. Calculated relationship between the normalized trapping force acting on pill A and the strip length.

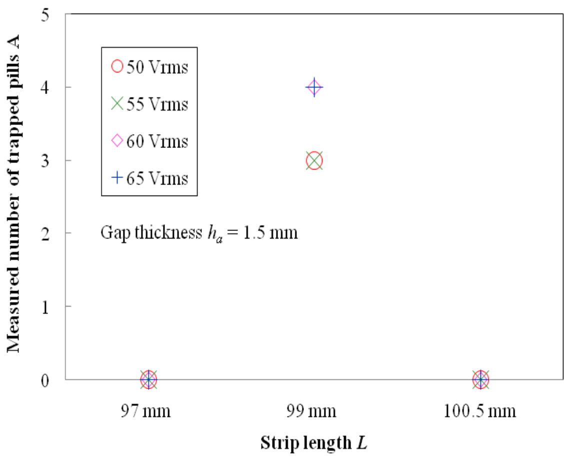


Figure 6. Measured number of trapped pills A for different strip lengths at resonance for different input voltages.

SUMMARY

We have proposed and explored the method to trap particles by the W-shaped ultrasonic actuator. The operating mechanism has been clarified by the FEM calculation of sound field and acoustic radiation force, and confirmed by experiment. Some trapping characteristics of the actuator have been measured and calculated. The W-shaped actuator proposed in this work may be used in the pick-up and transportation of particles such as medicine pills.

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