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High speed non-contact transport of small object in air through ultrasonic traveling field excited with parallel vibration plates

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***Abstract*—In precision manufacturing industry and pharmaceutical field, a method to manipulate micro parts and drugs without contact has become one of the key technologies. It is well known that particles can be trapped at the nodal points of acoustic standing waves if the particles are much smaller than the wavelength of the standing wave. In this paper, we have introduced a new configuration of the vibration system for generating traveling ultrasonic fields and succeeded in the non-contact transport of polystyrene sphere. The waveguide was composed of two parallel flexural vibration plates with a position shift of a quarter wavelength. The sphere was levitated at the nodal position of the vertical standing wave in the waveguide and transported by the traveling wave component in the horizontal direction. The transportation distance and speed were 40~50 mm and 293~543 mm/s, respectively.**

Keywords—non-contact transport, ultrasonic levitation, flexural vibration, traveling wave, standing wave, phase shift

I. Introduction

Non-contact manipulation and transport of small objects such as electronic components and micro mechanical parts are highly required in order to improve the production throughput and reduce the damage during the process. Conventional levitation techniques have difficulties to be applied for these purposes. Air levitation needs a bulky system including air compressor and piping [1]. Magnetic/electric method generates undesirable magnetic/electric fields on the target objects and is applicable on for the magnetic/electric materials [2][3]. On the other hand, ultrasonic levitation is capable for solving most of these problems because it can handle any materials and has good controllability with electrical signal [4][5].

Let us consider a standing wave field excited between a vibrator's end surface and a reflector as show in Fig. 1. If a small object is placed near the node of the sound pressure field, static force called 'acoustic radiation force' appears in the direction from the antinode to the node of the sound pressure. The object sufficiently smaller than the wavelength is captured at the node [6]-[8]. This phenomenon is known as 'ultrasonic levitation.'

The authors have reported several ultrasonic levitation methods for non-contact transport of small objects and droplets [9-11]. In this paper, for efficient linear transport, we propose a novel vibration system to generate traveling ultrasonic fields. Experimental demonstrations of high-speed transport and levitation experiment of chip parts are demonstrated.

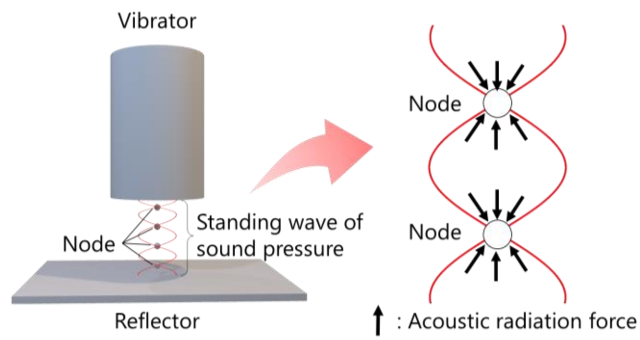

Fig. 1. Principle of ultrasonic levitation.

II. Principle

First, we explain the method for acoustic traveling wave synthesis. Two flexural vibration plates are placed in parallel as illustrated as Fig. 2. Both the upper and lower vibration plates are designed so that fringe mode flexural vibration occurs at the frequency of f. Here, the flexural vibration is approximated with a sine wave for simplicity. The wavelength of the standing wave vibration on the plate is defined as λ. The upper plate is shifted by $\lambda/4$ with respect to the lower vibration plate in the x-axis direction. The z-axis is set in vertical to the plates. Spacing between the plate is D. The lower plate is vibrated with a phase shift of $\mp\pi/2$ with respect to the vibration of the upper plate. The sound pressure P_U, expressing the standing wave between the two plates when only the upper plate is excited, is expressed by

$$P_U = P \sin k_x x \sin \omega t \cos k_z z, \qquad (1)$$

where P is the amplitude. On the other hand, the lower plate's vibration induces sound pressure P_L between the plates as

$$P_L = \pm P \cos k_x x \cos \omega t \cos k_z z. \qquad (2)$$

The wave numbers k_x and k_z in the x-axis and z-axis directions are given by

$$k_x = 2\,\pi/\lambda, \qquad (3)$$
$$k_z = 2\,\pi/(2D/n) = n\pi/D. \qquad (4)$$

Here, n is the mode number. Thus, the sound pressure distribution $P(x,z)$ when both of the vibration plates are excited simultaneously is expressed as the superposition of the two standing waves (1) and (2):

$$\begin{aligned} P(x,z) &= P_U + P_L \\ &= P\sin k_x x \sin\omega t \cos k_z z \pm P\cos k_x x \cos\omega t \cos k_z z \\ &= P\cos(k_x x - \omega t)\cos k_z z \quad \text{(phase shift:}-\pi/2) \\ &\quad -P\cos(k_x x + \omega t)\cos k_z z \quad \text{(phase shift:}+\pi/2) \end{aligned} \tag{5}$$

These result show that traveling wave in the x-axis direction and standing wave on the z-axis direction is synthesized, and the propagation direction of the traveling wave is switched by the phase difference of the excitation.

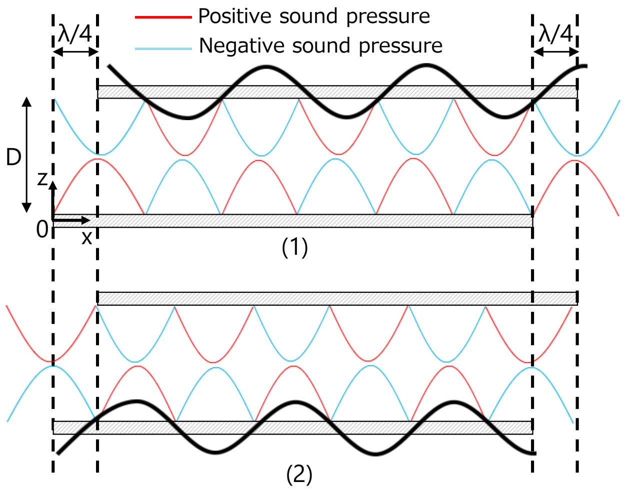

Fig. 2. Sound pressure distribution when only one side vibration plate is driven: (1), upper; (2), lower.

III. EXPERIMENTS NON-CONTACT TRANSPORT

Experimental setup for non-contact transport is shown in Figs. 3 and 4. Each plate is excited using Langevin transducer with stepped horn. The phase of the AC voltage applied to the lower vibrator (Transducer 2) was shifted with respect to that of the upper vibrator (Transducer 1) using a two-phase function generator. Both the upper and lower vibration plates are made of duralumin, and the lengths were chosen to resonate in one dimensional flexural vibration of the 8th mode at 26.7 kHz. The dimensions of the vibration plates are 99, 30, 2 mm in length, width and thickness. The plates are attached to the stepped horn with screws at the position of the vibration antinode (10.1 mm from the end). The upper vibration plate is shifted in the horizontal direction by a quarter of the wavelength of the vibration (6 mm). The interval *D* between the vibration plates are set to 7~8 mm so that a standing wave with one node in the z-axis direction is generated. The admittance characteristics of the transducers are shown I Fig. 5 as well as the relation between the driving current and the vibration velocity measured at 26.76 kHz. Since there was a difference between the force factor (ratio of the current to the vibration velocity) and the peak values of the admittance, the applied voltages were adjusted so that vibration amplitudes of the plates exhibited the same level. In this experiment, polystyrene sphere with a diameter of 3 mm and a weight of 0.4 mg was used as objects to be transported, and transportation experiments in the x-axis positive and negative directions were performed.

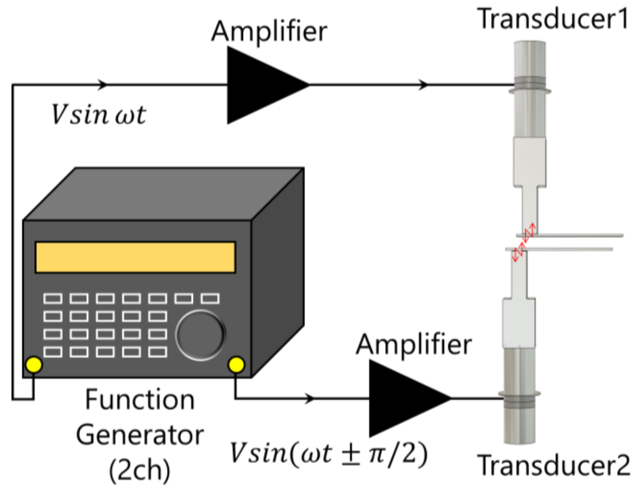

Fig. 3. Excitation method of two transducers with phase difference.

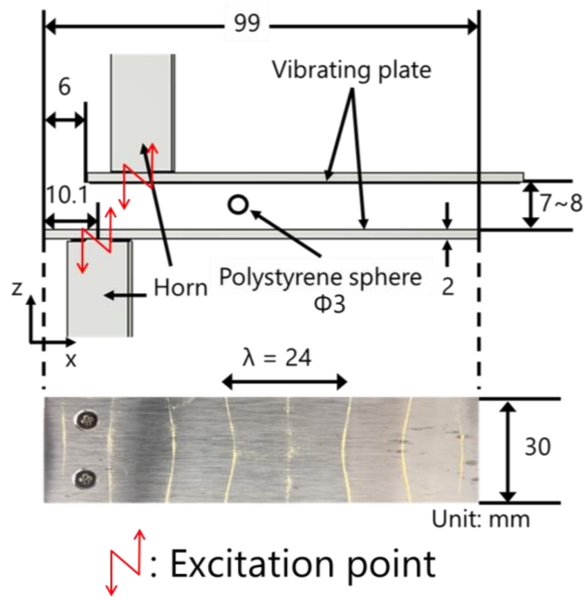

Fig. 4. Details of vibration plates.

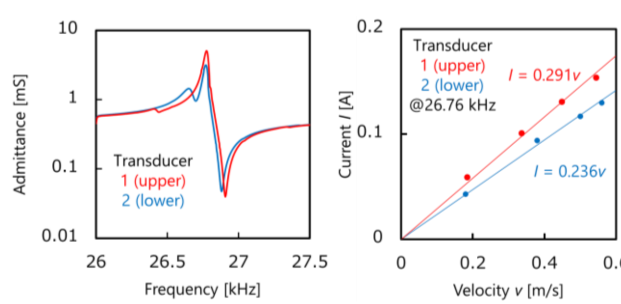

Fig. 5. Admittance characteristics (left) and force factors of transducers measured at 26.76 kHz (right).

A sphere was placed gently around the nodal line using a tweezer. Fig. 6 shows the movement of the polystyrene sphere, which was observed using a high speed camera. Many shots taken every 10 ms are superimposed in the picture. The non-contact transport of the polystyrene sphere with the traveling distance of approximately (1) 50 mm and (2) 40 mm were successfully recorded. Temporal changes in the horizontal velocity were obtained from Fig. 6 and plotted in Fig. 7. Exponential fitting curves drawn in the figure shows that the moving speed of the polystyrene sphere with a mass of 0.4 mg reached the terminal speed of (1) 293 mm/s and (2) 543 mm/s in around 0.2 s, respectively.

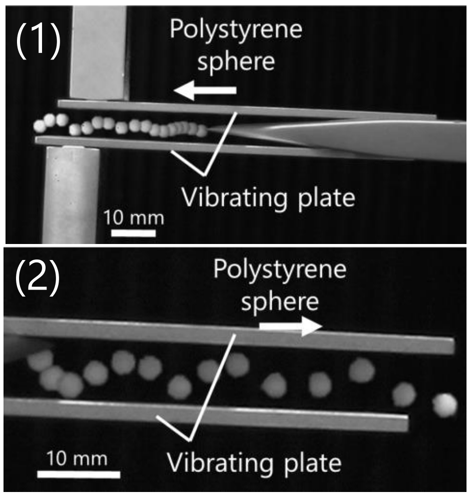

Fig. 6 Photo of the transportation trajectory of a polystyrene sphere between the vibrating plates taken at every 10 ms: (1), left direction; (2), right direction.

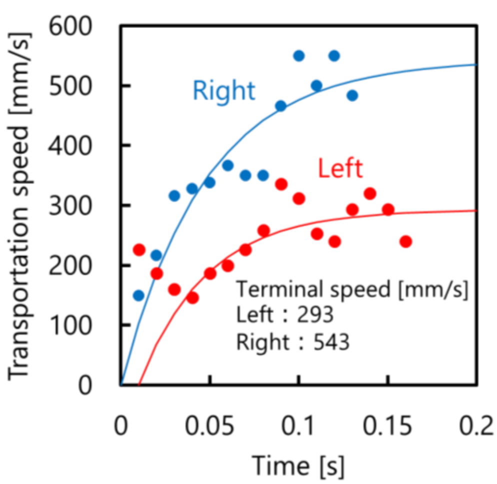

Fig. 7 Temporal change in transportation speed of particle.

IV. Levitation of Chip Parts

In addition to the experiment with polystyrene sphere, levitation of the chip parts was tried. Fig. 8 shows the experimental setup, which consists of a bolt-clamped Langevin transducer and a reflector. In this experiment, five transducers with different frequencies as shown in Fig. 9 were employed. Three different chip parts shown in Fig. 10 were tested: 1608, 1.6x0.8x0.8 mm; 0603, 0.6x0.3x03 mm; 0402, 0.4x0.2x0.2 mm. Fig. 11 demonstrates how the chip part 0402 is levitated between the end of horn and the reflector. Relation between the frequency and the ship size was experimentally discussed.

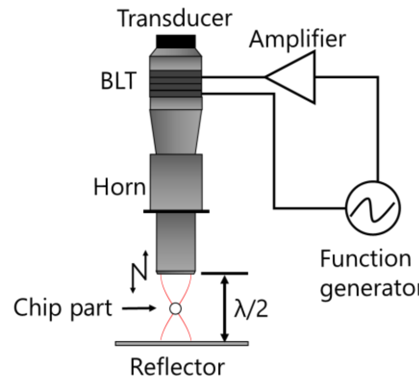

Fig. 8 Experimental setup for levitation of chip parts.

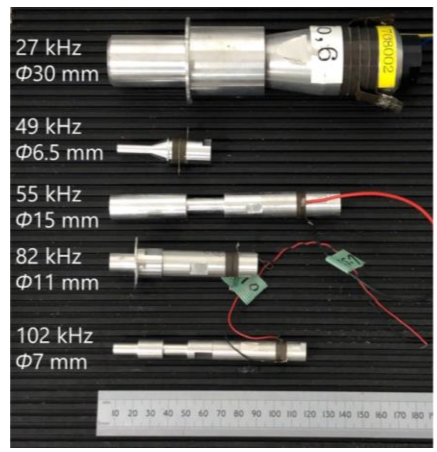

Fig. 9 Transducers used in the experiment.

Fig. 10 Photo of the chip parts.

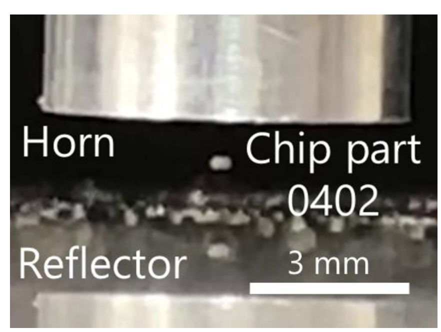

Fig. 11 Photograph of levitating a chip part 0402.

Fig. 12 summarizes the relationship between the frequency and the size of the levitated objects. Here, the minimum sound pressure level required for the levitation was recorded and plotted in the figure. The sound pressure was calculated from the vibration velocity of the horn end. The vibration velocity was calculated from the drive current and the force factor using the measured force factors of the transducers shown in Fig. 13. Chip part 1608 could be levitated at all frequencies from 27 kHz to 102 kHz, while 0603 could not be levitated at 27 kHz. Chip part 0402 was levitated only at 27 and 49 kHz. As the size of the chip parts become smaller, levitation at lower frequency become impossible. It is easily concluded that there is a certain relationship between the wavelength in air and the size of chip parts. However, shape of the part may cause a complexity.

TABLE I summarizes the relationship between the wavelength and the value divided by the thickness of the chip part. In this table, the numbers at which the chip parts were successfully levitated are shown in bold. If the size of the object is too small with respect to the wavelength, it is not levitated. The sound pressure level for the non-contact transport of polystyrene sphere is also plotted in Fig. 12. It is understood that 15 dB higher sound pressure level is required for levitating the chip part 1608 at 27 kHz.

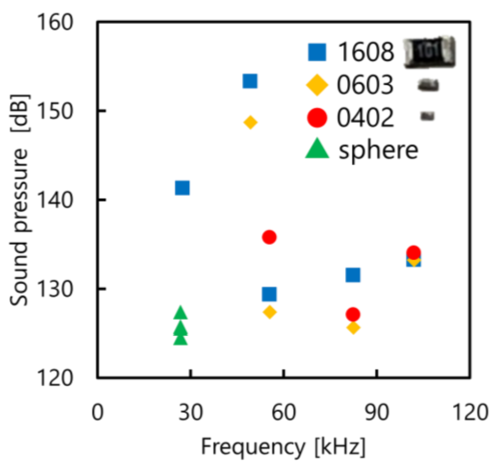

Fig. 12 Relationship between frequency and size of levitating objects.

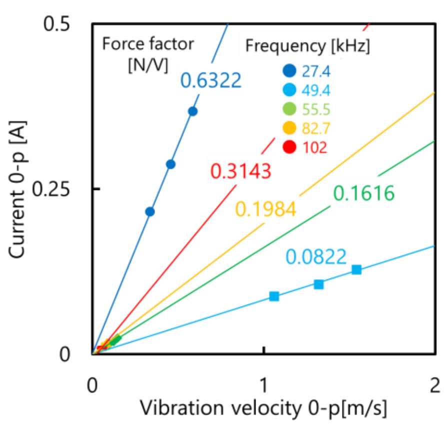

Fig. 13 Relationship between frequency and size of levitated object.

TABLE I. RATIO OF AIR WAVELENGTH TO CHIP PARTS SIZE

Frequency [kHz]	27.4	49.3	55.5	82.4	102
Wavelength of air [mm]	12.4	6.89	6.13	4.13	3.33
Wavelength / 0.8	**15.5**	**8.60**	**7.65**	**5.17**	**4.16**
Wavelength / 0.6	41.36	**22.9**	**20.4**	**13.8**	**11.1**
Wavelength / 0.3	62.0	34.4	**30.6**	**20.7**	**16.7**

V. CONCLUSIONS

In this paper, we have introduced a new vibration system for generating traveling ultrasonic fields, and succeeded in non-contact linear transport of a polystyrene sphere with the terminal speed of 293 mm/s (left direction) and 543 mm/s (right direction). Through the experiments with chip parts of different dimensions, we found a relationship between the ultrasonic frequency and the chip size to be levitated. We also evaluated the minimum sound pressure levels required for levitating chip parts of different dimensions. The chip size is becoming smaller every year, and vibration system working at over 100 kHz will be required in near future.

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