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Plate-shaped non-contact ultrasonic transporter using flexural vibration

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ABSTRACT

We developed a plate-shaped non-contact transporter based on ultrasonic vibration, exploiting a phenomenon that a plate can be statically levitated at the place where its gravity and the acoustic radiation force are balanced. In the experiment, four piezoelectric zirconate titanate elements were attached to aluminum plates, on which lattice flexural vibration was excited at 22.3 kHz. The vibrating plates were connected to a loading plate via flexible posts that can minimize the influence of the flexure induced by heavy loads. The distribution of the vibration displacement on the plate was predicted through finite-element analysis to find the appropriate positions of the posts. The maximum levitation height of this transporter was 256 μm with no load. When two vibrating plates were connected to a loading plate, the maximum transportable load was 4.0 kgf.

1. Introduction

In logistics industry and transport systems in factories, objects are often manually transported using pallets, where considerable thrust is needed for heavy load due to the friction force between the pallets and the floor. To reduce the friction, non-contact transport systems based on air bearing have been developed [1], but they required large air compressors and air tubes with sufficient amount of clean air. One of the promising candidates to solve this problem is the technique based on near-field acoustic levitation (NFAL). With this effect, a planner object can be levitated above a vibrating plate via a small air gap due to the acoustic radiation force generated by the ultrasonic field in the gap. There have been many reports to apply the NFAL to transporting silicone waters on large glass plates of liquid crystal display [2–6]. Here, we discuss a non-contact pallet table, where vibrating plates are levitated on a flat floor with acoustic radiation force.

We have so far reported two types of NFAL-based non-contact stages: a sliding table with two triangular cross-sectional guide rails [7] and a self-running bidirectional slider with an aluminum rectangular frame [8]. These stages exploit the traveling waves propagating along the stator guide rails or the slider itself, which induces acoustic streaming along the air gap, and a thrust force is generated to the slider through the viscosity force of air [9,10]. Traveling waves can be generated by two vibrating elements with a two-phase drive as well [7,8]; one of the vibration elements acts as a generator of sound waves, and the other as an absorber. We have also investigated an ultrasonically levitated slider for a self-running sliding stage for linear movement [11] as well as a non-contact moving two-dimensional stage [12] without guide rails required in the conventional ultrasonically levitated tables [7,8]. However, these rail-free transporters are applicable only to light objects.

In this paper, an NFAL-based plate-shaped non-contact transporter for relatively heavy loads is demonstrated. Four piezoelectric zirconate titanate (PZT) elements were attached to an aluminum plate, on which lattice flexural vibration was excited at 22.3 kHz. Two or four vibration plates were bearing an object with a loading plate, as illustrated in Fig. 1. To minimize the influence of the deflection induced by heavy loads, the vibrating plates were connected to the loading plate via flexible supporting posts. With no load, the maximum levitation height of this transporter was 256 μm. When two vibrating plates were connected to a loading plate, the maximum transportable load of 4.0 kgf was achieved.

2. Configuration of vibrating plate

The configuration of the self-levitation vibrating plate is shown in Fig. 2a–c. The vibrating plate consisted of a square aluminum plate ($2 \times 78 \times 78\ \mathrm{mm}^3$) and four PZT elements ($1 \times 18 \times 18\ \mathrm{mm}^3$; C-203, Fuji Ceramics). The PZT elements, bonded to the aluminum plate using epoxy, were polarized in the thickness direction. The

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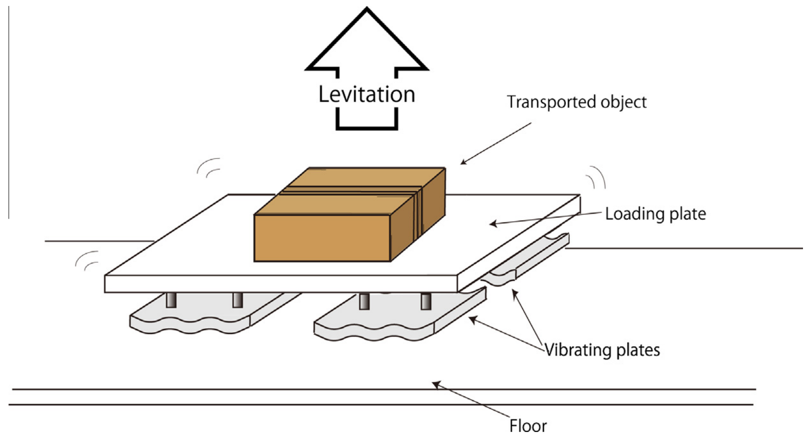

Fig. 1. Concept of self-levitating plate.

mass of the vibrating plate was as light as 42.2 g (68.0 N/m^2). By applying an alternating voltage to the PZT elements, lattice-mode flexural vibration at 22.3 kHz was generated in the aluminum plate, which induced the acoustic radiation force downward to the flat floor.

The dimensions of the aluminum plate and the PZT elements, the locations of the four PZT elements on the aluminum plate, and the flexural vibrating mode were determined with FEA simulation (ANSYS 11.0) [13] so that the vibration displacement amplitude of the vibrating plate was maximized to obtain large levitation force. Fig. 3 shows the simulated optimal distribution of the vibration displacement amplitude, where four nodal lines were observed in both *X* and *Y* directions at the resonance frequency of 23.2 kHz. Suitable positions of the PZT elements to maximize the average vibration amplitude over the entire vibrating plate were in every half wavelength of the lattice flexural vibration. The optimal size of the PZT elements (18 mm) was equal to the half wavelength of the flexural vibration.

3. Characterization of the flexural vibrations

The displacement amplitude distribution of the lattice-mode flexural vibration on the prototype was measured using a laser Doppler vibrometer (LDV), as shown in Fig. 4. The vibration mode expected through the FEA (Fig. 3) was successfully excited in the prototype vibrator at 22.3 kHz. All the PZT elements were excited in phase. The flexible posts for connecting the vibrating plate to the loading plate should be fixed at the nodal position of the plate because (1) the flexural vibration on the vibrating plate should not be suppressed and (2) the vibration should not be conveyed to the loading plate. Thus, the positions of the four posts were set, as shown in Fig. 4, to the four points (indicated as "P") on the nodal lines.

Fig. 5 shows the dependence of the total driving current to the four PZTs on the normal vibration velocity at the edge of the vibrating plate. The force coefficient, i.e. the slope of the dependence, was ~0.59 N/V. Using this value, the vibrating velocity can be estimated simply by measuring the current.

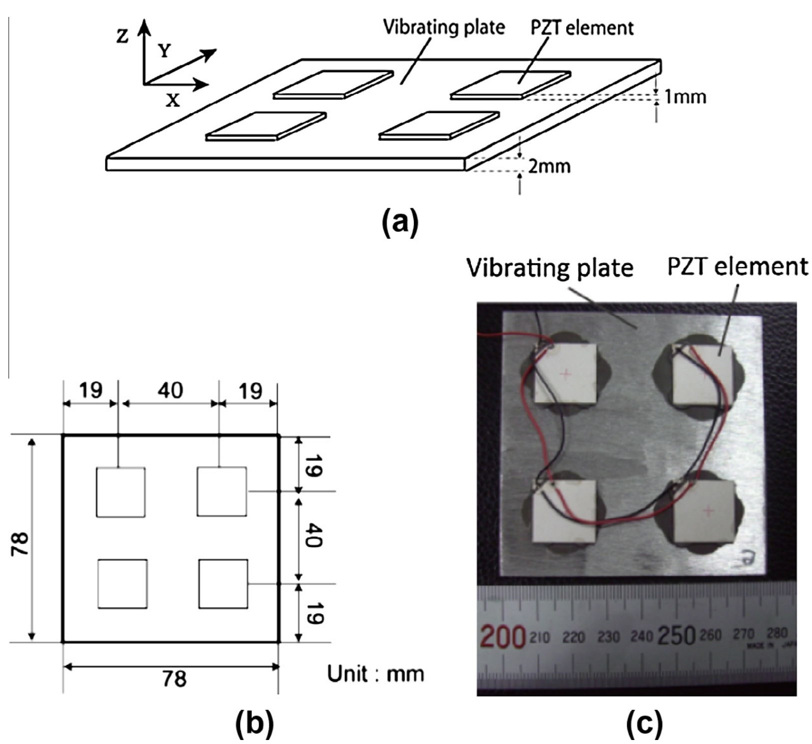

Fig. 2. (a) Configuration, (b) location of the PZTs, and (c) photograph of the vibrating plate.