Letters

New Type of Linear Ultrasonic Actuator Based on a Plate-Shaped Vibrator with Triangular Grooves

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***Abstract*—This paper presents a new type of linear ultrasonic actuator that can drive a slide by ultrasound. The ultrasonic actuator consists of a metal plate with uniform triangular grooves, multilayer piezoelectric vibrator, and supporting structure. The multilayer piezoelectric vibrator is used to excite a flexural vibration in the metal plate that is adjusted to lie horizontally. When the metal plate vibrates, a glass slide on it is levitated in the vertical direction and linearly driven along the length direction. Experimental characteristics of the prototype are presented here. This is the first report case of using the sound field that is generated by a grooved metal plate, to drive a slide levitated by acoustic radiation force.**

I. Introduction

Acoustic viscous force may be used to drive and stabilize an object levitated by acoustic radiation force and acoustic viscous force. The ultrasonic actuators that use the acoustic viscous force generated by a traveling wave or standing wave sound field have been proposed and developed for the applications in linear noncontact transportation systems and high-speed rotary motors [1]–[8]. In previous works, two actuators have been used to drive a levitated object in linear noncontact transportation systems. One uses a metal plate with traveling wave flexural vibration generated by two Langevin transducers [4], [5]. Another uses a tapered metal plate with standing wave flexural vibration generated by one piezoelectric transducer [8]. When the actuators in [4], [5], and [8] are used for long distance noncontact transportation, multiple identical structures need to be connected in series. However, in the connecting parts, there exist regions in which the driving force (acoustic viscous force) on slide is opposite to the transportation direction, or very close to zero. If slide length is not much larger than the wavelength of the flexural vibration, the slide cannot pass through these connecting parts due to the dragging force.

To develop a structure that is fit for long distance noncontact transportation, a new mechanism is proposed in this work, which uses the sound field generated by a grooved metal plate to drive a levitated object. Due to the tence of the grooves, the fluid resonance between the slide and radiation surface becomes possible if shape and size of the grooves can be designed properly.

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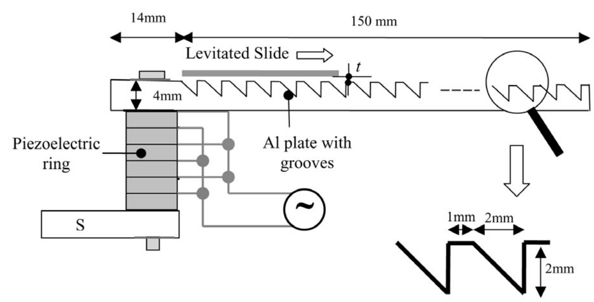
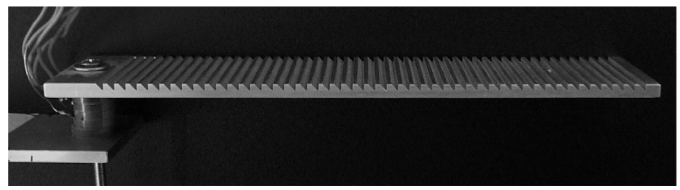


(a)



(b)

Fig. 1. (a) Construction and (b) photo of the proposed actuator.

II. Structure and Operating Mechanism of Proposed Actuator

Fig. 1(a) and (b) shows the construction and dimensions of the proposed actuator. A grooved aluminum plate with a size of 164 mm × 38 mm × 4 mm is used as a stator of the actuator, and a multilayer piezoelectric vibrator is bolted onto the end of the aluminum plate to excite a flexural vibration in the plate. Identical triangular grooves are used, and their size is shown in Fig. 1(a). The interval distance between two neighboring grooves is 1 mm. In the stator, the part with grooves is 150-mm long and the vibration excitation part without grooves is 14-mm long. The multilayer piezoelectric vibrator is formed by six pieces of piezoelectric rings with an outer diameter of 12 mm, inner diameter of 6 mm, and a thickness of 2 mm. The piezoelectric rings have a piezoelectric charge constant d_{33} of 325×10^{-12} m/V and mechanical quality factor Q_m of 2000. The actuator is mounted on a stage via an aluminum plate S, and the stator is accurately adjusted to lie horizontally. The slide on the stator is an object with a planar bottom surface such as a piece of glass.

When an alternating current (AC) voltage whose frequency is near to the resonance frequency of the actuator is applied to the piezoelectric vibrator, it can be observed that the slide is levitated in the vertical direction and driven in the horizontal direction. The moving direction of the slide is from the vibration excitation part to another end of the stator.

Due to the triangular grooves, the thickness of the air gap between the levitated slide and slant radiation surface is not uniform. A nonuniform acoustic field may be formed in all of the grooves. The location with a thin air gap has a strong vibration; and the one with a thick air gap has a weak vibration. This generates micro eddying stream on the bottom surface of the slide. Within the acoustic boundary layer on the bottom surface, the micro eddying stream is in the direction of decrease of the sound field or increase of the groove depth. This micro eddying streaming may generate an acoustic viscous force that drives the slide to move [8]–[11]. The acoustic radiation force in the horizontal direction due to an oblique incidence of the sound wave onto the bottom surface and the energy loss during the reflection also may contribute to the driving force [12].

From the above analysis, it is known that the slide experiences a driving force as long as there are vibrating grooves under it, and the direction of the driving force may be controlled by the direction of the slant surface of the grooves. This simplifies the design of long distance noncontact transportation systems. With this structure, multiple actuators may be connected together simply without the regions that drag the slide back, if the slant surfaces of the grooves in different actuators have the same direction. Also, the multilayer piezoelectric vibrator may be fixed at an arbitrary location along the middle line of the grooved plate.

III. Experimental Results and Discussion

In the following experiments, slide displacement means the displacement that the slide moved from the position shown in Fig. 1(a) to stopping position, and slide speed means the average speed within the range of the displacement. The slide speed and displacement were measured at constant driving frequency and temperature of the piezoelectric vibrator. By this, the phase difference between the input voltage and current was kept constant at different measuring points. The driving frequency and maximum temperature used in the experiments were 92.94 kHz and 31°C, respectively. The temperature was monitored by an infrared thermometer with a laser spot of 1.2 mm in diameter (Keyence, IT2-50 and IT2-02).

The dependencies of the slide displacement and speed on the input electrical power were measured for a glass slide with a mass of 0.17 g and size of 24 mm × 24 mm, and the results are shown in Fig. 2. It is seen that the slide speed is linearly proportional to the input power, and the slide displacement increases with increasing the input power.

According to the mechanism analysis in Section II, the driving force on the slide must be proportional to the square of vibration velocity of the stator [8]. Meanwhile,

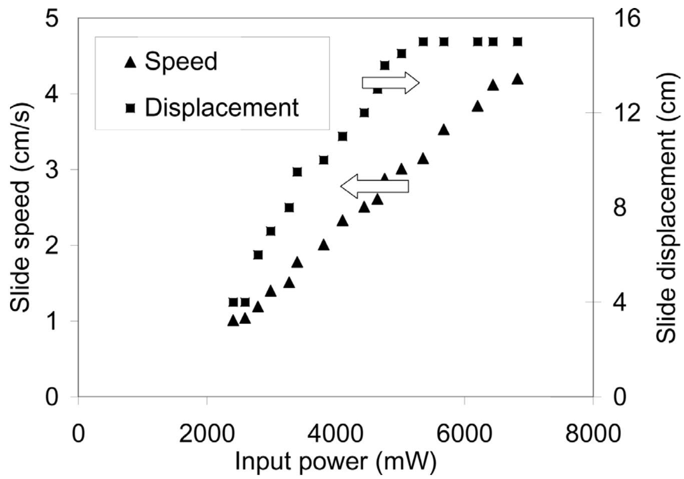


Fig. 2. Dependencies of the slide speed and displacement on the input power.

it is known that the drag force on the moving slide is proportional to the slide speed when the slide speed is not very high [9]. Due to the balance between the driving and drag forces, the slide speed is proportional to the square of the vibration velocity. The input power of an actuator is proportional to the square of its vibration velocity when the load of the actuator is not very heavy. Hence, the slide speed of this actuator is linearly proportional to the input power.

From Fig. 2, it also is known that the segment away from the vibration excitation part in the stator has not enough vibration to levitate the slide if the input power is not sufficient. Therefore, to transport the slide for a long distance, it is necessary to enlarge the vibration of the actuator.

The effects of the weight per unit area of slide on the slide speed and displacement were measured for different input power, and the results are shown in Fig. 3(a) and (b). To get different weight per unit area of slide, stacked glass slides were used in the experiment. It is seen that, when the weight per unit area of slide is too large, the slide has no motion. This is because acoustic radiation force is not large enough to suspend the slide in that case. Therefore, improvement of the vibration excitation part is necessary to transport a slide with large weight per unit area.

IV. Conclusions

This work provides a new type of noncontact linear ultrasonic actuator based on a plate-shaped vibrator with uniform triangular grooves, which is capable of transporting light planar objects. Compared with the noncontact linear ultrasonic actuators developed previously, this structure allows a long transportation distance, possible utilization of fluid resonance, and flexible and simple arrangement of the vibration excitation part. Design of fluid resonance and improvement in vibration excitation and

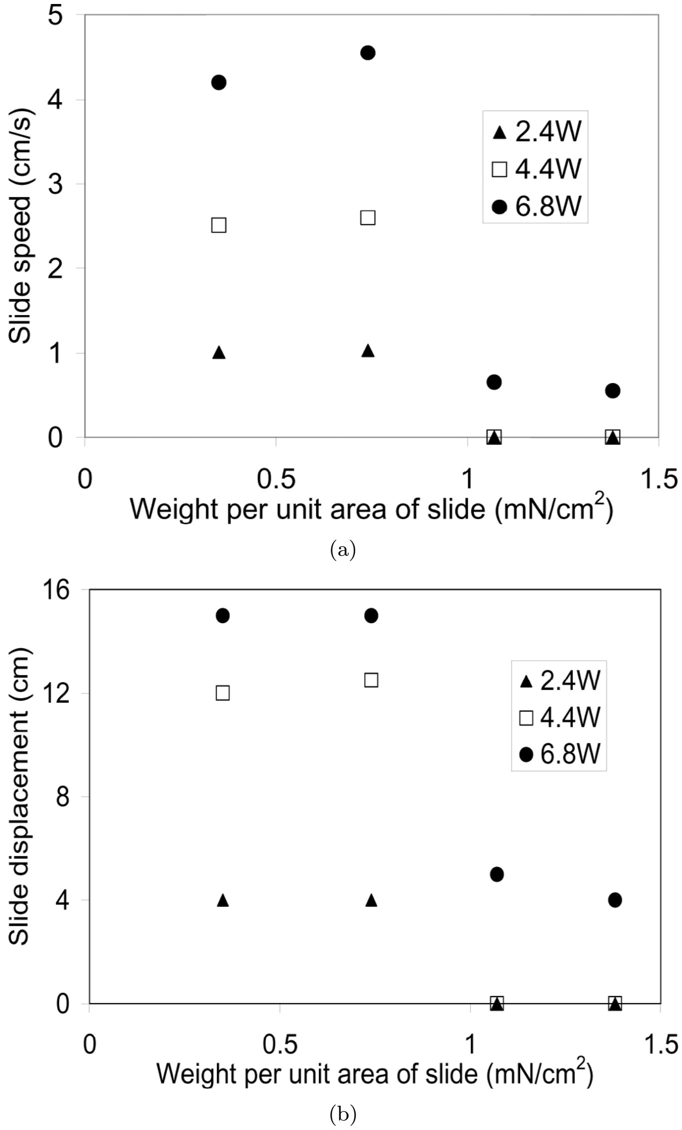


Fig. 3. Effects of the weight per unit area of slide on the slide speed and displacement. (a) Slide speed, (b) slide displacement.

slide stability will be conducted for the applications in noncontact ultrasonic transportation in air and water.

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