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Levitation characteristics and vibration behavior in ultrasonic levitation actuators

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Abstract

This study introduces a non-contact ultrasonic levitation actuator aimed at reducing friction-induced surface damage and positioning errors in precision motion systems. The actuator consists of a stainless-steel inertial mass, a multilayer piezoelectric element, and an aluminum plate. When driven by a high-frequency voltage, the plate generates a squeeze film of air that enables micrometer-scale levitation. To avoid audible noise observed in previous levitation actuators operating in the 10 kHz range, the proposed actuator is driven at ultrasonic frequencies above 20 kHz. Experiments were conducted by varying plate thickness from 1.0 mm to 2.0 mm in 0.2 mm increments under a sinusoidal voltage of 5 Vpp and drive frequencies between 20 kHz and 40 kHz. The maximum levitation height of approximately 44 µm was achieved at 25.5 kHz using a 1.0 mm thick plate with a vibration amplitude of 5.7 µm. These results clarify how plate thickness influences drive frequency and levitation performance, demonstrating the potential of ultrasonic levitation actuators for compact, high-precision positioning applications.

Levitation actuator, Piezoelectric actuator, Levitation characteristics

1. Introduction

In recent years, space constraints have become an issue in factories due to the increasing size of manufacturing equipment. Robots capable of micro-scale motion are receiving increasing attention in various research fields. Among various positioning mechanisms, inchworm-type robots are utilized[1]. Current research efforts are focused on the development of a freely movable inchworm-type robotic system that integrates electromagnetic actuators with piezoelectric elements (piezos) [2]. The locomotion of the robot is achieved through a combined mechanism involving the attraction and release of an electromagnetic coil and the extension and contraction of a piezo. However, this method presents issues, including surface damage caused by friction during the dragging operation of electromagnetic components, as well as a reduction in positioning accuracy. Therefore, we are investigating a levitation actuator as a non-contact mechanism. Previous studies on levitation actuators have employed drive frequencies in the 10 kHz range, resulting in undesirable acoustic noise[3]. In this paper, we aim to develop and characterize an ultrasonic levitation actuator operating beyond the audible frequency range, thereby eliminating noise during levitation.

2. Levitation actuator

Figure 1 shows the structure and operating principle of the proposed levitation actuator. The levitation actuator is composed of a stainless-steel inertial mass, a piezo, and an aluminum plate, which are bonded using a cyanoacrylate adhesive. The inertial mass used in the actuator has a height of 8 mm, a diameter of 20 mm, and a mass of 20 g. The piezo (Tokin, AE0505D16DF) exhibits a maximum displacement of 17.4 µm, when a DC voltage of 150 V is applied. It has a length of 20 mm, a crosssection of 5 mm by 5 mm, and a mass of 5 g. The aluminum plate shown in Figure 1 has a thickness of 1 mm, a diameter of 30 mm, and a mass of 2 g. In our previous study, a plate with the same diameter but a thickness of 3 mm was used, and levitation was achieved at driving frequencies between 4 kHz and 15 kHz.

When a high-frequency voltage is applied to the piezo, it vibrates rapidly in the vertical direction. This vibration generates a repulsive force between the plate and the ground surface, forming an air film known as the squeeze film. This phenomenon, referred to as the squeeze film effect, enables the actuator to levitate several micrometers above the ground. The levitation height is defined as the average value of the instantaneous vertical displacement of the plate, while the vibration amplitude is defined as the difference between the maximum and minimum vertical displacement of the plate.

The levitation is measuted by a laser displacement sensor. The laser beam is directed onto the top surface of the plate at a position within 1 mm from the plate edge to obtain the instantaneous vertical displacement, levitation height, and amplitude of the plate accurately.

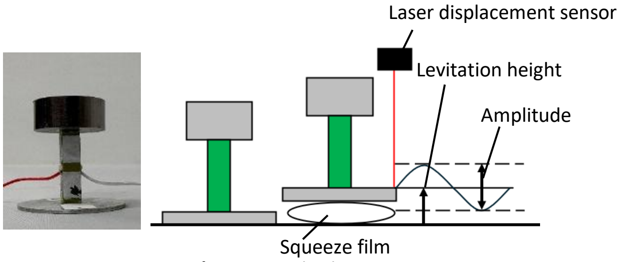

Figure 1. Levitation actuator

3. Experimental setup

The voltage from an oscillator is passed through an amplifier and applied to the piezo. A sinusoidal voltage of 5.0 Vpp, with a frequency ranging from 20 kHz to 40 kHz in 0.5 kHz increments, is applied to the piezo. The instantaneous vertical displacement of the plate is measured by a laser displacement sensor (Keyence, LK-H053). Both the vertical displacement and the applied voltage are recorded on an oscilloscope and a data recorder.

The levitation height defined as the average vertical displacement is obtained over a one-second interval. The vibration amplitude defined as the difference between the maximum and minimum vertical displacement is calculated, which is the peak-to-peak value corresponds to the vertical displacement of the plate.

4. Results and discussion

Figure 2 shows the experimental results of the characteristics of the levitation height for plates with different thicknesses. The horizontal axis and vertical axis denote the drive frequency and the levitation height, respectively. For the levitation actuator equipped with a 1.0 mm thick plate, levitation begins at approximately 25 kHz, and the maximum levitation height of 44.0 µm is achieved at 25.5 kHz. Beyond this frequency, the levitation height gradually decreased.

The levitation height using other plates with different thickness is smaller than that obtained by the 1.0-mm-thick plate. The frequency obtained by an individual plate thickness depends on the thickness of the plate. The second highest levitation height of 25.3 µm is achieved with the 2.0-mm-thick plate at 30.0 kHz.

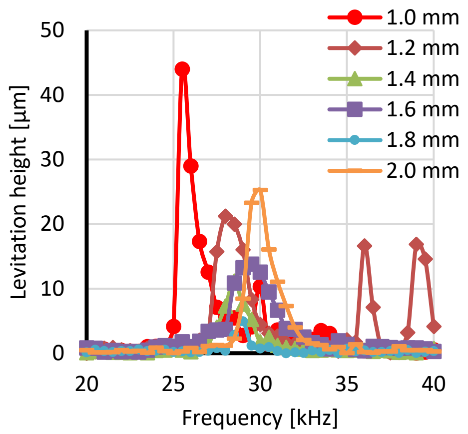

Figure 2. Levitation characteristics

Figure 3 summarizes the relationship between plate thickness, maximum levitation height, and the corresponding drive frequency. For each thickness condition, the levitation height is measured across a range of drive frequencies, and the maximum levitation height together with its corresponding frequency is identified. As the plate thickness increases, the maximum levitation height tends to decrease. The drive frequency at which the maximum amplitude occurs lies within the range of approximately 25 kHz to 30 kHz for all tested thicknesses.

To examine variations in vibration behavior due to plate thickness, the vertical displacements of the 1.0-mm and 2.0-mm plates are measured. Figure 4 shows the vertical displacement of the 1.0-mm and 2.0-mm plates. The 1.0-mm-thick plate exhibits an amplitude of 5.7 µm with a period of 0.039 ms, while the 2.0-mm-thick plate shows an amplitude of 3.1 µm with a period of 0.033 ms. The phase relationship between the applied voltage and the vertical displacement exhibits different phenomena. The 1.0-mm-thick plate lags the voltage by approximately 142.3 degrees, whereas the 2.0-mm-thick plate leads it by 58.3 degrees. These results indicate that plate thickness significantly affects the capacitive and inductive characteristics of the levitation actuator, thereby altering both the resonance frequency and phase response.

At the resonance frequency, the plate oscillates with its maximum amplitude under sinusoidal excitation, resulting in the maximum levitation height. When the plate vibrates with an applied voltage of 5 Vpp, the DC component of the applied voltage does not affect the vibration of the plate. This DC component originates from the capacitive characteristics of the piezo and the output impedance of the amplifier. Consequently, the phase difference between the applied voltage and the vertical displacement is caused by the characteristics of the squeeze air film.

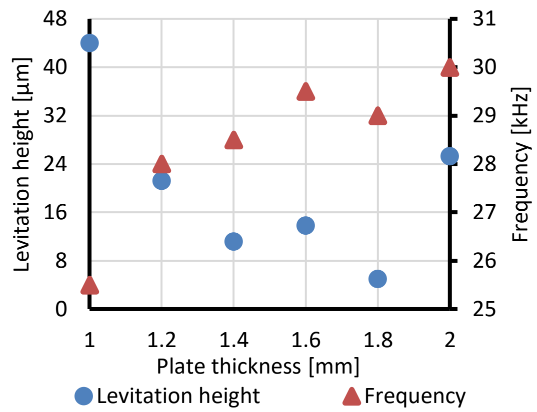

Figure 3. Relationship between plate thickness, Levitation height, and frequency

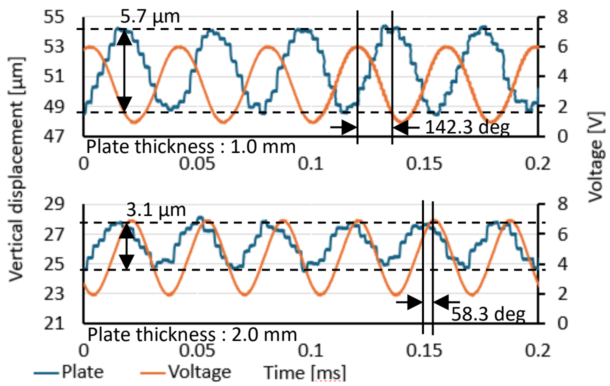

Figure 4. Drive voltage and vertical diaplacement of plates.

5. Conclusion

This study demonstrated the performance of an ultrasonic levitation actuator driven at frequencies above 20 kHz to avoid audible noise. Experiments using plates of varying thickness revealed that thinner plates produce larger vibration amplitudes and greater levitation heights, with the 1.0-mm plate achieving a maximum height of 44 µm at 25.5 kHz. As the plate thickness increases, both the amplitude and levitation height decrease, confirming the strong influence of structural stiffness on squeeze-film dynamics. These results provide practical design guidance for the development of compact, high-precision ultrasonic levitation actuators.

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