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Actuation Force Measurement Mechanism for Non-contact Ultrasonic Suspension

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Abstract. In near-field levitation, an object can be levitated vertically upward above vibrating surface of an ultrasonic transducer. In this case, a repulsive force acts on the object. On the other hand, it has been reported that a minute object can be suspended vertically downward under the vibrating surface with a small gap in the air. We call this phenomenon ultrasonic suspension. Under the suspension, an attractive force acts on the object. When an object is suspended, there is restoring force, which pulls the object to the center of the vibrating surface. Our aim is to characterize the actuation forces under the suspension. Simultaneous measurement of vertical and horizontal actuation forces is required. A servo type measuring mechanism was proposed. A 1 DOF mechanism with a cantilever and a voice coil motor (VCM) was fabricated as a prototype. The prototype was calibrated and utilized for measurement of vertical actuation force. The result showed enough accuracy and repeatability. Then, a 2 DOF actuation force measurement mechanism was fabricated. The mechanism was consisted of a base to fix the object and two thin wires to support the base. Position of the base was controlled by three VCMs based on PID control. The ultrasonic suspension actuation forces were characterized successfully.

Introduction

Recently, a non contact handling technique that uses ultrasonic levitation phenomenon as a means of transporting semiconductor substrates or LCD glass substrates has been considered [1-5]. In particular, the near-field levitation phenomenon has been observed. Near-field levitation is the phenomenon in which a planar object can be levitated upward above a vibrating surface with a gap of tens micrometers. Theoretical analysis considering viscosity has revealed that in near-field levitation, a force acting on a circular plate reverses from repulsive to attractive with increasing levitation distance [2].

In contrast to ultrasonic levitation, a planar object can be suspended downward below the vibrating surface without contact [6]. This phenomenon is called ultrasonic suspension. In both cases, the horizontal actuation force, which attracts the object to the center of the vibrating surface when there is horizontal misalignment, acts as the restoring force. However, in the case of ultrasonic suspension, the actuation force has not yet been measured in detail. In this study, a mechanism for servo-type actuation force measurement was developed to experimentally measure actuation forces and their characteristics.

Ultrasonic Suspension

Vertical Actuation Force Figure 1 (a) shows the positional relationship between the vibrating surface of an ultrasonic transducer and a circular plate in ultrasonic suspension. The planar object can be suspended without contact when it approaches the vibrating surface from below. The suspension force disappears when the ultrasonic vibration stops. Therefore, the object can be easily released.

Regarding actuation forces, it has been reported that the air viscosity in a narrow space influences the behavior of sound waves [2]. Based on the analysis considering viscosity, the principle of vertical actuation forces has been proposed as follows: When the height of the space (the gap) is smaller than the viscous boundary layer between a piston sound source and a planar object, the air in the space cannot be extruded by the downward moving source owing to air viscosity. As a result, the air is pressurized and its pressure induces a repulsive force. When the gap is larger than the layer, the air in the narrow space is extruded to the outside by the downward moving source. In the case of the upward moving source, the extruded air cannot flow into the space because of fluid resistance, which is higher than that in the case of the downward moving source. As a result, the time-averaged pressure in the space decreases and is lower than that of the surroundings. The decreased pressure induces an attractive force, as illustrated in Fig. 2.

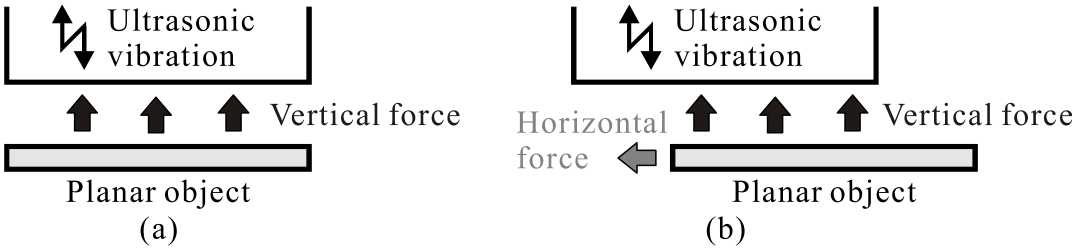

Figure 1 Schematic illustration of ultrasonic suspension

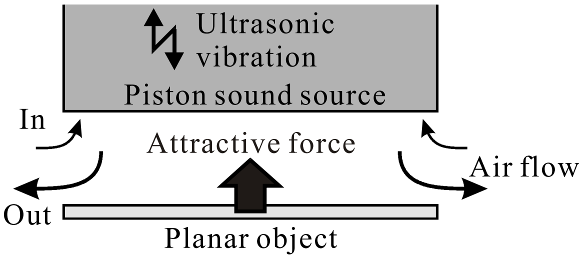

Figure 2 Principle of ultrasonic suspension

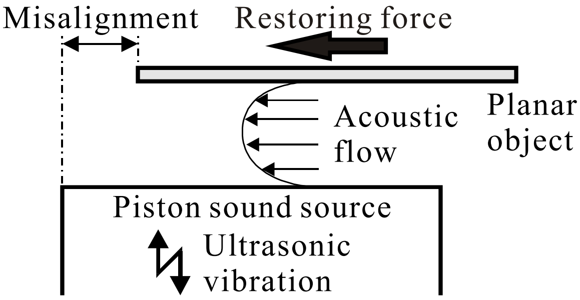

Figure 3 Principle of horizontal actuation force

Horizontal Actuation Force As shown in Fig. 1 (b), when there is a horizontal misalignment between the vibrating surface and planar object, the horizontal actuation force acts as restoring force on the object, which attracts the object to the center of the vibrating surface. This force can stabilize suspended objects.

The origin of this force has been considered to be the acoustic flow of the sound pressure distribution between the object and vibrating surface in near-field levitation [7]. The acoustic flow between the object and vibrating surface was visualized and confirmed using lycopodium. It has been estimated that the acoustic flow has a velocity gradient along the vibrating direction, as shown in Fig. 3, and induces a Stokes viscous force. The Stokes viscous force acts as the restoring force. If there is no horizontal misalignment between the objects and vibrating surface, the Stokes viscous force balances the entire area. Therefore, the force does not act on the object. On the other hand, if the object is displaced horizontally, the sound pressure distribution in the narrow space changes. Because of this change, the acoustic flow disequilibrates the Stokes viscous force. At this time, the force acts in the opposite direction of the displacement. In addition, it has been confirmed by theoretical analysis and experiments that the horizontal actuation force increases with the horizontal displacement. However, the force decreases when the displacement increases beyond a certain value. We predicted that the same phenomenon would occur in ultrasonic suspension.

Langevin Type Ultrasonic Transducer

A bolt-clamped, Langevin-type ultrasonic transducer, shown in Fig. 4, was utilized in our experiment. In order to enhance the vibration amplitude, a horn was coupled to the top of the transducer. A cap was attached on the top of the horn. Changing the cap, diameter of vibrating surface that faces the suspended object. A flange was located on the vibration node and fixed on a stage. The transducer vibrated in the longitudinal vibration mode. The resonance frequency was about 28 kHz. The frequency of the driving voltage of the transducer was controlled by a resonance frequency tracing system [8], because the resonance frequency fluctuates due to operating conditions, such as applied voltage, transducer temperature, and others.

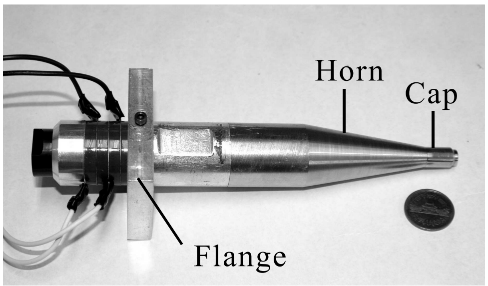

Figure 4 Photo of Langevin type ultrasonic transducer

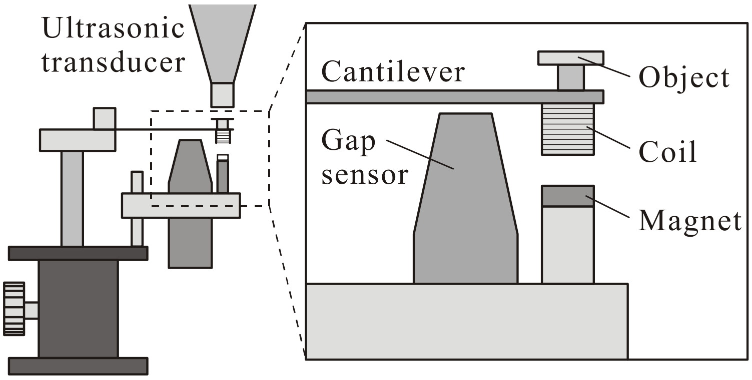

Figure 5 Schematic illustration of servo type 1-DOF actuation force measurement mechanism

A Servo Type 1-DOF Actuation Force Measuring Mechanism

In previous research, vertical direction actuation force characteristics have been measured by convenient way with a cantilever. By the nature of the mechanism, the actuation force must be estimated from displacement of cantilever. There are some problems such as the change of positional relationship between vibrating surface and the objects. It needs to be improved to keep the relationship.

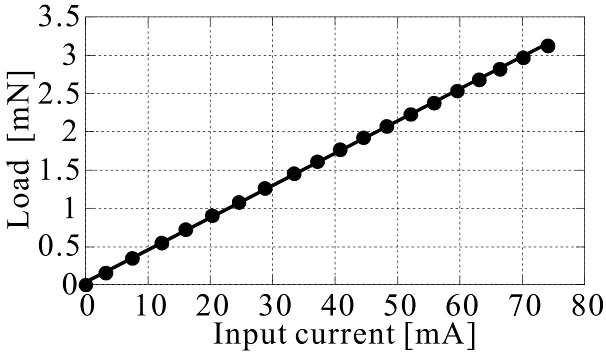

Figure 6 Relationship between input current into the coil and load

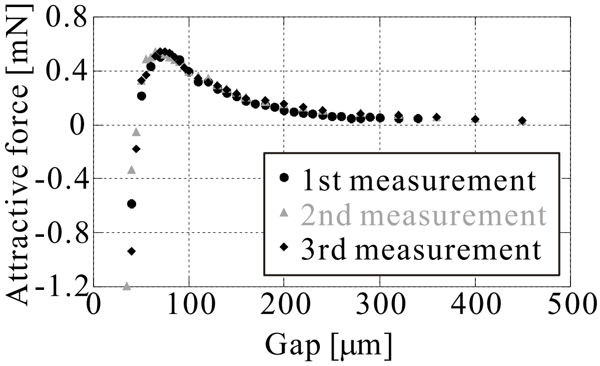

Figure 7 Relationship between attractive force and gap

Figure 5 shows configuration of proposed measuring mechanism. The object was fixed on the cantilever, whose size was 60 mm x 10 mm x 0.05 mm. The cantilever displacement was measured by a gap sensor with resolution of 50 nm. To configure a VCM, a coil was equipped on the top of the lever and a neodymium magnet with the size of ϕ1 mm x 2 mm was fixed below the coil. The coil had 200 turns winding and was 7 mm in diameter and 7 mm in length. The VCM compensated the displacement of the lever. With applying PID control, displacement of the cantilever caused by actuation force was controlled by the VCM. Concretely, the gap sensor detected displacement of the lever. Then PID controller controlled input current into the VCM to keep displacement of the lever constant. As a result, displacement of the lever was constant on static state whether the actuation force was acting or not. The problems caused by displacement of the lever had been solved. Estimation of actuation force is conducted from input current of actuator instead of displacement of the lever. Relationship between coil current and the load to the top of the lever was observed under the control. The observation result is plotted on Fig. 6. It can be seen that the relationship was linear. Three trial measurement results of vertical actuation force using the relationship is shown in Fig. 7. For the graph, negative value means repulsive force. Diameter of both the cap and object was 6 mm. Vibration amplitude was 3 $\mu m_{p\text{-}p}$. As the figure shows, near the *Z*-axis zero point, the vertical force increased as the gap increased. In this region, therefore, stabilized suspension can be performed vertically. The three measurements were conducted on different days. The three results coincided with each other. Applying the servo type mechanism leads to high repeatability and accuracy.

A Servo Type 2-DOF Actuation Force Measuring Mechanism

We confirmed that the servo type mechanism has high repeatability and accuracy, as mentioned above. So an actuation force measurement mechanism, which can measure vertical and horizontal direction actuation force simultaneously, has been fabricated. Figure 8 shows the schematic illustration of a servo type 2-DOF actuation force measuring mechanism. A base for fixing objects was hanged by two piano wires. The transducer was approached to the object horizontally. Three VCMs were placed around the base. To configure the VCM, coils were fixed on the base and a yoke with 2 magnets was arranged so that each coil can cover one finger of the yoke without contact. PID control was applied as a control law to input current of VCMs. VCM1 was for controlling X-axis direction translational motion, VCM2 and 3 were for controlling Z-axis direction translational motion and rotational motion revolving about Y-axis. The change of steady current inputted to VCMs, which caused by the actuation force was measured for estimating the actuation force. Meanwhile displacement of the base was detected by optical sensors, which were placed opposed side of each VCM. Sensitivity of the sensor was 0.1 m/V. In this way, it can be possible that positional relationship between vibrating surface and the object keep constant as a condition arranged before experiment.

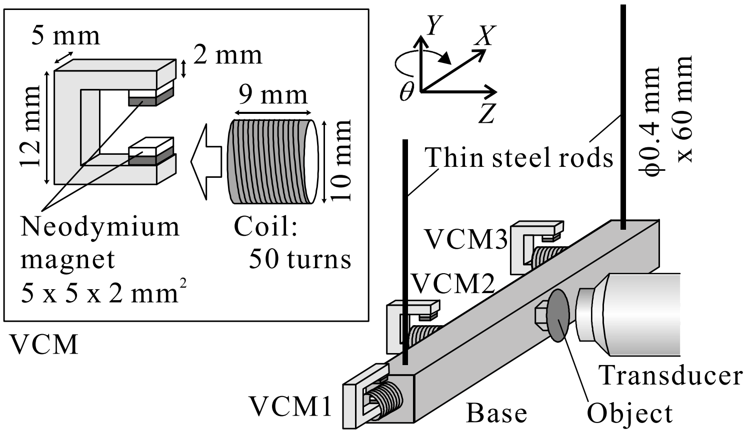

Figure 8 Schematic illustration of servo type 2-DOF actuation force measurement mechanism

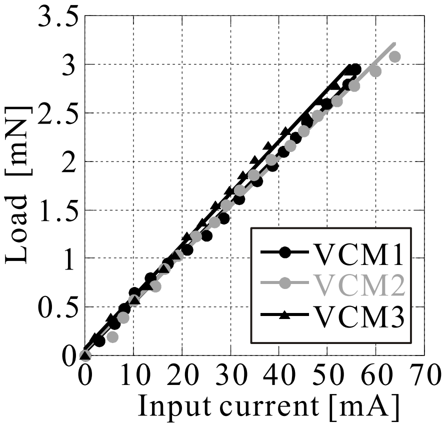

Figure 9 Relationship between input current and load of VCMs

Originally, positional relationship between vibrating surface and the object during ultrasonic suspension is similar to Fig. 1. But as shown in Fig. 8, with rotating positional relationship 90-degree, there is no need to take account of the gravity. Since vertical and horizontal motions are controlled, vertical and horizontal direction actuation forces can be measured simultaneously. Figure 9 shows the relationship between input current and load of VCMs. In range from 0 to 50 mA, characteristics of VCMs can regard as almost linear. Estimation of actuation forces stands on these characteristics. Offset current into VCMs are adjusted so as to fit the range of linear. It means that load of VCMs and restoring force of wires balanced. Measurement can be carried out stable before and after changing the direction of the actuation forces in this way.

Parallelization and origin definition had to be conducted to keep a constant gap and a positional relationship with high repeatability. At first, a stage was precisely leveled to fix the ultrasonic transducer. Secondly, the transducer was replaced with a laser displacement sensor, as shown in Fig. 10. The parallelism between the stage and the planar object was arranged precisely. If the output signal of the displacement sensor does not change when the surface of the planar object is scanned horizontally, parallelization is completed. Then, the parallelism between the vibrating surface and the object was adjusted, as shown in Fig. 11. The transducer was placed in contact with the object at two points by arranging the orientation of the object. When the transducer contacts the planar object, the integral signal of the PID controller increases rapidly as a characteristic of PID control. With the change of the signal, the steady current into VCMs increases. This can make it easy to discriminate when contact has been made. If the contact points about the *Z*-axis are the same, it means that the parallelization is completed. Next, the vertical origin in the coordinates, namely a zero gap, was defined, as shown in Fig. 12. The origin was defined as the contact point where the current increased rapidly while the transducer was lifted up slowly. Finally, the horizontal origin, namely the center point, was defined as shown in Fig. 13. Two opposing horizontal contact points were identified in the same manner as previously described. The middle point of the two was defined as the origin.

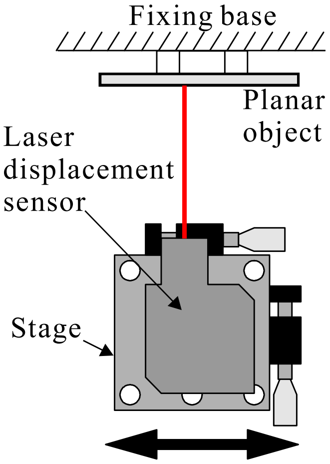

Figure 10 Parallelization of object and stage

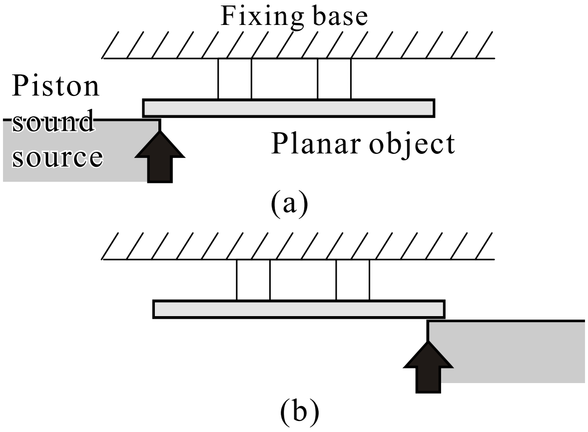

Figure 11 Parallelization of vibrating surface and object

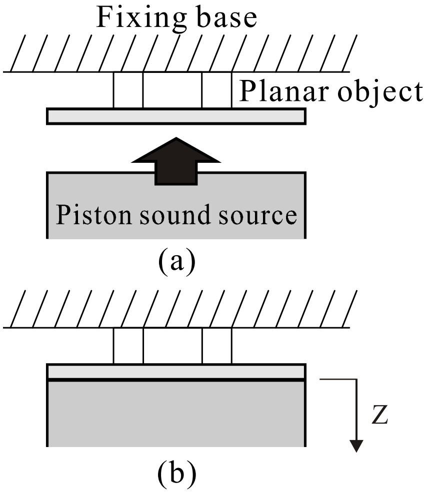

Figure 12 Z-axis zero calibration

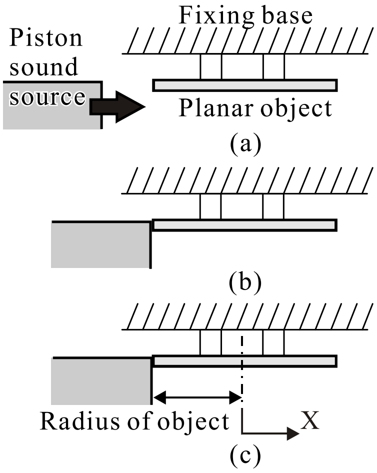

Figure 13 X-axis zero calibration

Actuation Force Measurement

Vertical and horizontal actuation force measurements were conducted with the servo-type 2-DOF actuation force measuring mechanism as trial. Only thin circular plate objects were used as the suspended object. Trial measurement result of vertical actuation force is shown in Fig. 14. Diameter of both the cap and object was 6 mm and vibration amplitude was 5 $\mu m_{p\text{-}p}$. Near the *Z*-axis zero point, the vertical force increased as the gap increased. In this region, therefore, stabilized suspension can be performed vertically. Relationship between the horizontal force and the center distance was obtained on trial. The center distance represents horizontal misalignment between the center of the vibrating surface and the object. Measurement result is shown in Fig. 15. Considering accuracy of coil current measurement, note that this result contains the assumption of linearity of coil current. Diameter of both the cap and object was 6mm and vibration amplitude was 5.1 $\mu m_{p\text{-}p}$. As shown in the figure, the horizontal actuation force was nearly in proportion to the center distance in the neighborhood of the X-axis zero point. In this region, therefore, stabilized suspension can be performed horizontally.

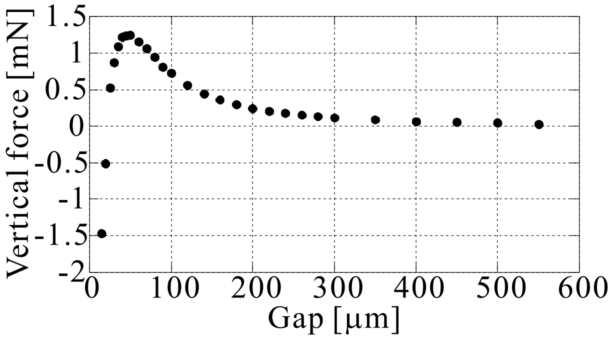

Figure 14 Relationship between gap and vertical force

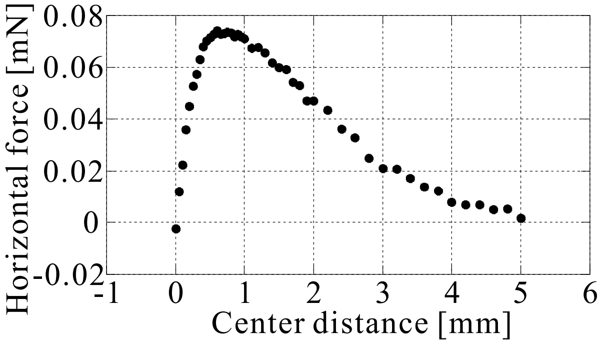

Figure 15 Relationship between center distance and horizontal force

Conclusion

To investigate ultrasonic suspension characteristics in detail, actuation force measurement mechanism was proposed. A 2 DOF servo type measurement apparatus was fabricated and calibrated. Using the mechanism, vertical and horizontal actuation force of ultrasonic suspension was observed on trial.

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