Evaluation of Fine Feed Table Positioning for Non-Contact Support based on the Squeezed-Air Effect

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The squeezed-air effect autonomously generates air pressures through high-frequency oscillations. We have proposed a novel positioning technique based on the squeezed-air effect to provide support and fine feed using a table under non-contact conditions. For this, a uniquely shaped table with a mortar-shaped bottom cross-section was designed. The table was floated and supported in balance with its weight by applying a pressure to the facing surfaces on both sides of the table bottom, and it was fed finely according to the pressure change at one side of the table. Excitation units were provided with angle adjustment mechanisms for the excitation surfaces. Such angle settings facilitated table support according to the table bottom inclination angle. Generally, the ability of the squeezed-air effect depends on the parallelism between the excitation and facing surfaces. The angle adjustment mechanisms also contributed to the improvement of parallelism. Piezoelectric elements were installed as excitation transducers. The relationship between the excitation amplitude and floating height of the table was examined. Subsequently, table positioning experiments were conducted with a step response. The target feed displacement was several tens of micrometers, and the estimated feed displacement was calculated based on the floating height and compared with experimental values.

1. Introduction

Positioning technologies are essential for micromachining. Recently, with the development of microelectromechanical system devices [1], the requirements for improved positioning have increased. In positioning devices, mechanisms composed of a ball screw and a rolling guide [2] are often used [3]. They are suitable for large and high-load machining. However, it is difficult to maintain high-precision positioning owing to the kinematic errors and sliding friction of the drive and transmitting elements. Solving these problems requires complicated equipment and difficult controls. That is, it is hard to mention that it is rational to achieve high positioning accuracies using screw feed units in micromachining for small sizes and light loads.

Although flexible mechanisms applying piezoelectric elements (PZTs) [4] are relatively small and ideal for micromachining, sliding friction caused by contact-based support and drive force reduces the kinematic accuracy. A typical example of a non-contact support is a mechanism using a magnetic force actuator. For example, there is a study [5] in which rigidity is secured by a flexible support and fine feed by a magnetic attraction force. However, magnetic forces generate magnetic fields and heat.

Therefore, a positioning technique using an air film support was considered. The squeezed-air effect autonomously generates static pressure by high-frequency oscillation. Therefore, it eliminates the need the need for an external pressure supply source. This effect was applied in studies on non-contact thrusting using dead weight [6] by levitating and supporting a table with an air film. The primary purpose of these technologies is to transfer objects; however, they can be applied to feed positioning with proper consideration.

We propose a positioning technique that enables table support and fine feed in a non-contact condition by applying the squeezed-air effect. A uniquely shaped table with a mortar-shaped cross section on its bottom was designed. The table support rigidity was obtained by balancing its weight by applying pressure on both sides at the bottom. Furthermore, by adjusting the pressure, an air film thickness difference was induced, and the table was finely fed. The excitation units have an adjustable mechanism for the angle of the excitation surface. Thus, it is possible to perform floating and fine feed experiments based on different table bottom inclination angles. The ability of the squeezed-air effect depends on the parallelism between the excitation surfaces and facing surfaces. Angle-adjustment mechanisms also contribute to the improvement of parallelism. In this study, prototypes of tables with different bottom inclination angles were designed with a targeted feed displacement of several tens of micrometers. Support and fine-feed experiments were conducted on table. The experimental values of feed displacement were evaluated in comparison with the estimated values.

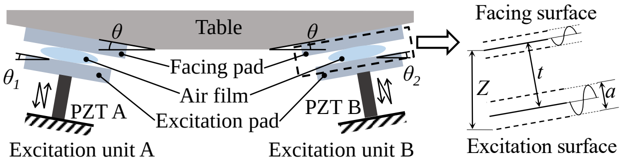


Fig. 1 Floating support mechanism

The estimated values were calculated geometrically based on the floating height.

2. Mechanism of floating support and fine feed

Figure 1 shows the floating support mechanism. Excitation units A and B were installed symmetrically opposite to the facing pads attached to the bottom of the table. The excitation units were composed of PZTs and excitation pads. PZTs oscillate the excitation pads at high frequencies with a sine wave. The table floats owing to the air film generated in the gap between the excitation pads and facing surfaces. The table has a mortar shape with an angle θ on both sides to support it in a wedge shape. θ_1 and θ_2 of excitation units A and B were adjusted for parallelism with respect to θ. The table was supported under excited conditions. Therefore, the film thickness t is defined as the difference between the center position of the excitation amplitude (a/2) and average position of the table oscillation amplitude based on the floating height Z. This is calculated using Eq. (1).

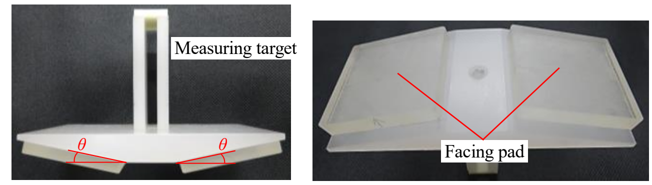
$$t = Z \cdot \cos\theta - \frac{a}{2} \tag{1}$$

The table is supported stationary by the air films generated by excitation units A and B, as shown in Fig.1, and the table is fed finely by the difference in film thickness caused by increasing and decreasing excitation amplitudes.

3. Apparatus of the table and fine feed, drive, and measuring system

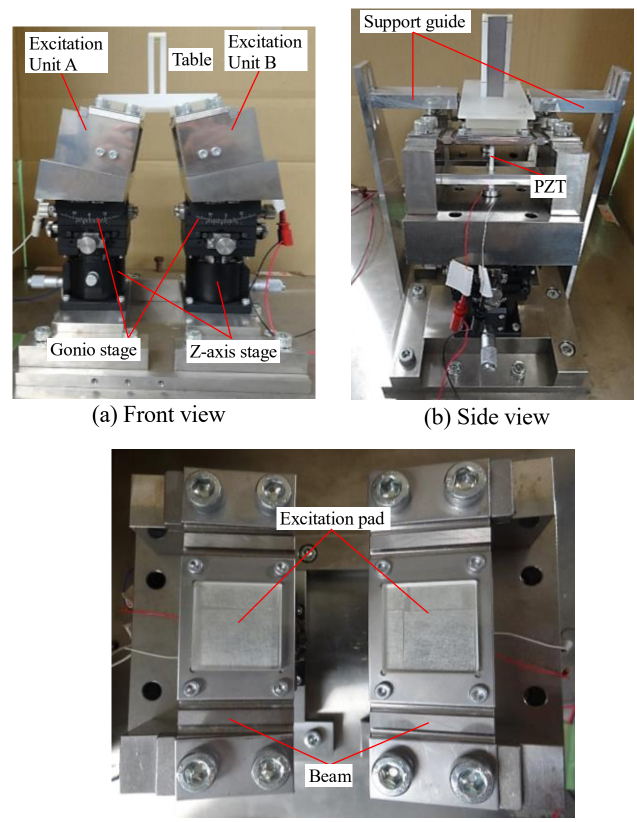
Figure 2 shows the configuration of the feed table. It was fabricated from polypropylene, with excitation pads on the bottom and a displacement measurement target on the top. The smoothness of the excitation and facing surface contributes to good pressure generation. Thus, glass planar substrates with a flatness of λ/10(λ = 632.8 nm) were used for facing pads (40 mm × 40 mm). Tables with θ = 10° and 12° were evaluated. The table surface dimensions are 100 mm × 50 mm, and the total weight is θ = 10°: 82.7 g and θ = 12°: 87.0 g.

Figure 3 shows the apparatus of fine feed. Figs. 3(a) and 3(b) show the state in which the table is mounted on excitation units A and B. Goniometric stages and Z-axis stages mounted at the bottom of both units allow the inclination angles θ_1 and θ_2 to be adjusted(see Fig. 1) relative to θ and the height of each unit. Fig. 3(c) shows the upper part of the excitation units. Glass planar substrates with the same precision as the facing pads (30 mm × 30 mm) were attached as the excitation pads. Excitation pads were fixed on the beam with elastic hinges. PZTs (AE0203D44H40) were installed such that preloads were applied to



(a) Front view (b) Bottom view.

Fig. 2 Fine feed table



(a) Front view (b) Side view

(c) Top view (without table)

Fig. 3 Apparatus of fine feed

the beam. By this mechanism, high-frequency oscillation amplitudes generated by PZTs can be stably transmitted to the excitation pads. Because the apparatus in this study was at the prototype stage, the table was supported only in the longitudinal direction. Therefore, support guides were installed to prevent the table from collapsing along the width. By attaching steel balls with extremely small diameters to the support guides, point contacts were established to prevent fine feed from being perturbed. Figs. 3(a) and 3(c) show the conditions without guides.

The frequency and amplitude of the voltage applied to PZT A and B can be adjusted individually by the 2-channel output function generator. The floating height and feed displacement of the table were measured using a capacitance displacement meter.

4. Properties of excitation amplitude and floating height

Figure 4 shows the relationship between the applied voltages V_A and V_B to PZT A and B and the excitation amplitudes a_A and a_B. The excitation frequencies f_A and f_B were set to be 2.0 kHz. The applied

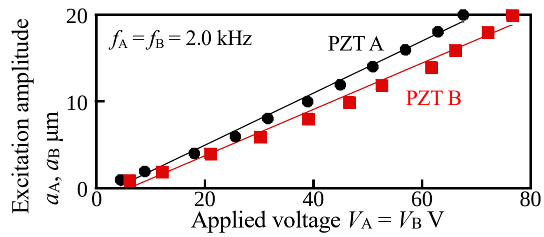


Fig. 4 Relationship between applied voltage and excitation amplitude

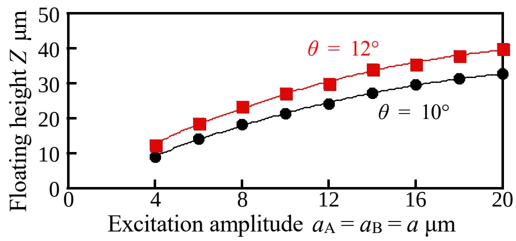


Fig. 5 Relationship between excitation amplitude and floating height

voltage represents the maximum of the peak-to-peak value, and the minimum voltage is 0 V. V_A and V_B were limited to 80 V or less owing to the PZT driver capability. Because the individual differences in PZTs and preloads were not similar, the excitation amplitudes with respect to the applied voltage were different for excitation units A and B. The relationship between V_A and a_A and V_B and a_B can be approximated by a linear function.

The table was floating supported by the simultaneous drive of PZT A and B. Fig.5 shows the relationship between $a_A = a_B =$ a and floating height Z. Because Z averages the sampling data for a certain period of time, it corresponds to the value obtained by table amplitude averaging. The ability of the squeezed-air effect depends on the parallelism between the excitation and facing surfaces. Therefore, the better the parallelism, the greater the floating height. Thus, the inclination angles θ_1 and θ_2 of the excitation units A and B were adjusted by trial and error so that the floating height could be increased as much as possible. The relationship between a_A, a_B and Z can be approximated by a quadratic function. Z can be estimated based on V_A and V_B from Figs. 4 and 5.

5. Positioning property

5.1 Estimation of fine feed

By applying an unsophisticated geometric approach to predict the table positioning ability, the feed displacement was simply estimated. Point O is defined at the center of the table and Points A and B are defined at the center of both facing surfaces, as shown in Fig. 6. When pressures P_A and P_B are applied to both surfaces, the table is supported horizontally with film thicknesses t_A and t_B. Next, increasing the pressure from P_A to P_A" causes the film thickness to increase from t_A to t_A' at Point A. Therefore, Point A lifts with the fulcrum at Point B, resulting in δ_x' in the first motion. However, δ_x' is negligible because $t_A' - t_A$ is miniscule compared to the length l between Points A and B. At this moment, Point A is higher than Point B. Therefore, in the second motion, the vertical displacement δ_z of $t_A' - t_A$ is distributed into a descent at Point A and an ascent at Point B; then the table is stable in

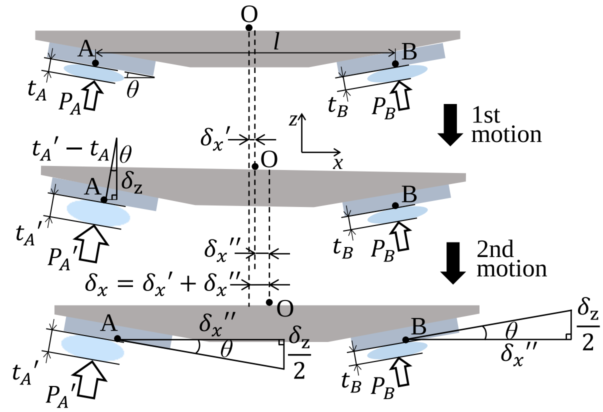


Fig. 6 Simplified estimation of table feed displacement

the horizontal state. δ_x" can be estimated based on the motion in which half of δ_z descended at Point A and ascended at Point B.

The feed displacement δ_x of this process can be calculated as the sum of δ_x'(= 0) and δ_x" using Eq. (2).

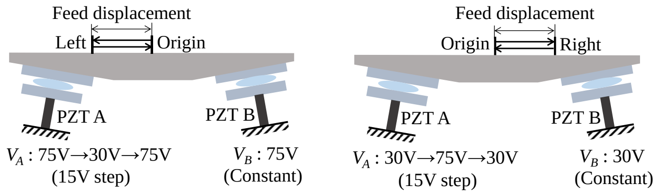
$$\delta_x = \frac{1}{2}(t_A' - t_A) \cdot \frac{\cos\theta}{\tan\theta} \tag{2}$$

According to Eq. (2), δ_x values with respect to $t_A' - t_A$ are 2.8 and 2.3 times for $\theta = 10°$ and 12°, respectively.

5.2 Fine feed experiment and discussion

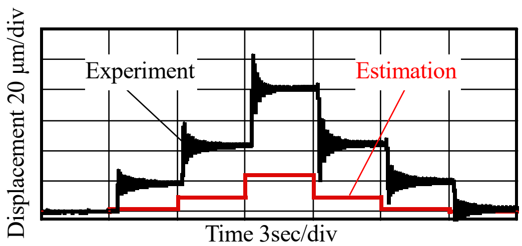
Figure 7 shows the condition of the table feed. Fig. 7(a) was set to 75 V for the applied voltages of V_A and V_B, and V_A was varied from 75 V to 30 V to 75 V in 15 V steps while the voltage of V_B was maintained constant. In this case, the table was fed from the origin to the left and back to the origin. Fig. 7(b) was set to 30 V for the applied voltages of V_A and V_B, and V_A was varied from 30 V to 75 V to 30 V in 15 V steps while the voltage of V_B was kept constant. In this case, the table was fed from the origin to the right and back to the origin. Figs. 8 and 9 show the step responses at $\theta = 10°$ and 12°. The table feed direction is shown in Figs. 8(a) and 9(a): origin → left → origin, and Figs. 8(b) and 9(b): origin → right → origin. The applied voltage was manually changed every 3 s.

The feed displacements were evaluated by comparing the experimental and estimated values. The ratios of the experimental to estimated values were 3.3 for the left direction feed and 3.2 for the right direction feed at $\theta = 10°$, and 2.6 for the left direction feed and 2.6 for the right direction feed at $\theta = 12°$. The mechanisms that cause the differences between the experimental and estimated values are discussed below. The estimated values were calculated based on the relationship between the excitation amplitude and floating height shown in Fig. 5. To examine this relationship, the parallelism adjustment on both sides of the table bottom was arbitrarily adjusted for excitation units A and B. In this case, the average parallelism is high for both units, but there is a possibility that the parallelism may be uneven for units A and B individually. For $\theta = 10°$ and 12°, the experimental values were larger than the estimated values. The reason for this is assumed to be that the parallelism of excitation unit A, for which the applied voltage (film thickness) was adjusted, was higher



(a) Origin → Left → Origin. (b) Origin → Right → Origin.

Fig. 7 Step feed condition



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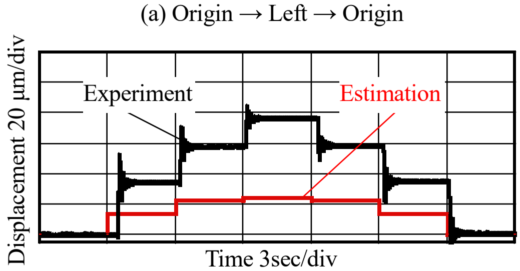
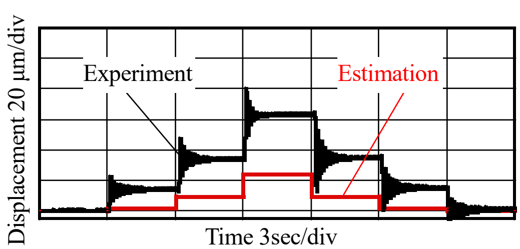
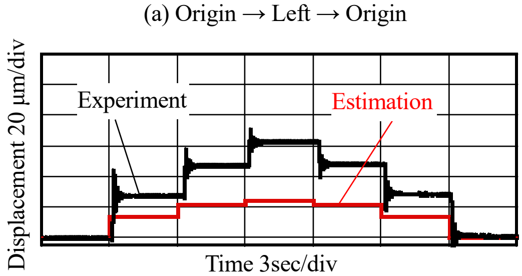


(b) Origin → Right → Origin

Fig. 8 Step response ($\theta = 10°$)



(a) Origin → Left → Origin



(b) Origin → Right → Origin

Fig. 9 Step response ($\theta = 12°$)

than that of excitation unit B. The feed displacements were almost the same for $\theta = 10°$ and 12°, regardless of the feed direction.

Overshooting observed upon changeover of the applied voltage is considered to be caused by an instantaneous increase or decrease in the film thickness. The maximum feed displacement in the experiment was 81 μm for a left direction feed of $\theta = 10°$ and the minimum was 63 μm for $\theta = 12°$ (equal in the left and right directions).

For both θ, the step displacement in the experiment gradually increased as the applied voltage decreased. On the other hand, it gradually decreased as the applied voltage increased. This is also the case for the estimated step displacement, in which the response properties of the two are qualitatively identical. As shown in Fig. 5, the change in floating height with the change in excitation amplitude is larger in the low excitation amplitude (applied voltage) range than in the high excitation amplitude range. In other words, this difference in the change rate is also reflected in the step displacement in the practical feed.

6. Conclusions

We proposed a positioning technique that enables table support and fine feed in a non-contact condition by applying the squeezed-air effect. A uniquely shaped table with a mortar-shaped cross section on its bottom was designed. The excitation units have an adjustable mechanism for the angle of the excitation surfaces. This enabled the adjustment of parallelism with the facing surfaces. The floating height and positioning properties of the table were examined, and abilities were discussed.

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