Ultraprecision Positioning by Preload Change of Lead Screws* (Characteristics of Fine Feed)

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Ultraprecision positioning is examined for a fine feed system utilizing the elastic deformation of lead screws accompanying the change in the preload in a double nut. The nonlinear deformation due to Hertzian contact of the ball screw can be ignored within a feed of $1\text{ }\mu\text{m}$ under an adequate initial preload. No effect of table load on nanometer-order displacement is observed in the range from 10 to 50 kg. The table displacement obtained under an increase in the preload coincides well with the result under a decrease in the preload. Feed control with preload change based on a one-to-one correspondence of preload change and displacement is effective for avoiding the hysteresis phenomenon of the piezoelectric actuator adopted as a deformable spacing part in a double nut. In addition, the preload can be used as a measure to detect the table displacement in place of a position sensor which sometimes shows unreliability owing to unstable performance in the nanometer region. The minimum step feed deduced from preload change is 1 nm for a sliding screw and 5 nm for a ball screw.

Key Words: Ultraprecision Positioning, Machine Element, Ball Screw, Sliding Screw, Double Nut, Preload Change, Fine Feed, Position Sensor

1. Introduction

According to a questionnaire⁽¹⁾ on ultraprecision positioning, lead screws are adopted as feed mechanisms in 51.9% of the cases, and this rate significantly exceeds that of 6.6% of friction drives which are placed in second rank. The reason for this is that lead screws are suitable for long distance feeding and an abundant store of technical knowledge regarding lead screws is available.

Ultraprecision positioning of nanometer order, however, cannot be realized so easily. For example, although a sliding screw is simple in construction, the fine motion required for ultraprecision positioning is very difficult due to the high friction on the screw threads. The above-mentioned questionnaire also reveals that the usage rate of ball screws and sliding

screws among the used lead screws is 80.6% and 16.2%, respectively. The reason why ball screws are the most widely used is their smooth movement based on small rolling friction. However, to realize nanometer-order positioning with ball screws, the nonlinear motion due to ball rolling at the starting time poses a problem⁽²⁾. Thus, a hydrostatic screw with a noncontact thread is considered suitable for ultraprecision positioning and much research on it has been conducted^{(3),(4)}. However, hydrostatic screws also have many drawbacks such as a complicated structure, low rigidity and very high manufacturing cost. Therefore, hydrostatic screws are uncommonly used in practice.

Under these circumstances, we have proposed a simple and practical method for ultraprecision positioning using ordinary ball and sliding screws⁽⁵⁾. By modifying the conventional method using lead screws with a constant preload on the double nut, the new method for fine feed utilizes the elastic deformation occurring in screws accompanying the preload change. This could apply for both ball and sliding screws because the principle of fine feed by elastic deformation of the screw has no relation to thread

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friction. In addition there is no need to use high-accuracy screws. It can also be expected to obtain reproducible positioning due to the fact that the elastic deformation is free from hysteresis and lost motion. Furthermore, this method has the advantage that the actual displacement gained as output is reduced compared to the spacing part expansion amount given as input, and the ratio of the output displacement to the input deformation can be varied by varying the spacing part stiffness. In this paper, to clarify the fine feed characteristics of this method, the initial preload effect in relation to the nonlinear deformation behavior of the ball screw and the table load effect is examined. Furthermore, the fine feed difference between calculation and experimental results is discussed by separating the fine feed into deformation components. Finally, the effectiveness of fine feed control by preload change is shown in addition to its availability for indirect displacement measuring and the minimum feed obtained by this method is examined.

2. Feeding Unit

Figure 1 shows the schematic view of the precision feed unit used here. On the lead screw, a piezoelectric stack (lead zirconate titanate: PZT) as the spacing part to be deformed and a sensor to detect the preload are inserted in the double nut. If the PZT length is changed, then the preload changes in the double nut which leads to the elastic deformation of threads and the screw shaft. As a result, the table connected to a nut is displaced slightly. Hence, this feed unit realizes ultraprecision positioning over a long traverse path in combination with coarse positioning by regular screw motion and fine positioning by preload change⁽⁶⁾. Both ball and sliding screws are used in this unit. The left side of the screw shaft is constrained to move in the axial direction, whereas the right side can move freely. The table can be connected to either the fixed-side nut 1 or free-side nut 2. When the table is connected to nut 1, less table displacement occurs. The table of mass 10.7 kg, is

Fig. 1 Schematic view of precision feed unit

guided by cross roller bearing.

The PZT is deformed through a drive amplifier which is controlled by a personal computer. Preload change that arises following the PZT deformation is detected by the steel ring sensor with attached strain gauges on its rim. The table displacement is measured with a laser scale of 8 nm resolution or a position sensor of noncontact capacitance type of 1 nm resolution. The measured values are sent to the personal computer.

The feed unit is mounted on a vibration isolation table with pneumatic springs and this setup is placed in an air-conditioned room. However, the air conditioner is not used here because sometimes its switching motion causes electric noise which prevents accurate measurement. The time required to perform the experiment is from two to four minutes and the room temperature change during this period is less than 0.1°C.

3. Influence of Initial Preload

The axial deformation of the ball screw against loading exhibits nonlinear behavior because of Hertzian contact between the balls and the screw groove. This effect on the fine feed is examined by changing the initial preload.

Figure 2 shows the table displacement when the preload is increased more than 250 N from the initial preload (loading) and decreased to the initial preload (unloading) continuously for three initial preloads of 300, 500 and 700 N. In this case, the table is connected to the free-side nut 2. The results for the sliding screw obtained under the same conditions are shown in Fig. 3 for comparison. The values calculated by the equation presented in a previous paper⁽⁵⁾ are also

Fig. 2 Influence of initial preload on table displacement (Ball screw)

Fig. 3 Influence of initial preload on table displacement (Sliding screw)

given in both figures. There is almost no identifiable difference in the displacement between loading and unloading of the preload with both ball and sliding screws.

With the ball screw, less displacement occurs under the high initial preload, and this is similar to the calculated result. However, the actual displacements become greater than the calculated values. The displacements against the preload increase of 250 N from the initial preloads of 300, 500 and 700 N are 2.7, 2.3 and 2.0 μm , respectively. The increase rate of the displacement decreases slightly as the preload increase. This is clearly observed when the initial preload becomes small. As a result, it is ensured that the nonlinearity of Hertzian contact deformation influences the fine feed characteristic. However, the nonlinearity of the table displacement is not so marked. Consequently, the displacement can be regarded as being almost linear within 1 μm feed. The actual fine feed range will be sufficient within 1 μm , because the positioning accuracy of 1 μm is not so difficult with the coarse positioning by the ball screw motion. When using the ball screw in this method, it is recommended to perform the fine feed within 1 μm under an adequate initial preload.

In the case of the sliding screw shown in Fig. 3, the table displaces linearly against preload change independent of the initial preload. The actual displacement exceeding the calculated value is the same as that of the ball screw. However, the slope of the displacement line becomes slightly smaller under a higher initial preload. This means that owing to the various errors which inevitably exist on the screw, a higher initial preload results in the increase of load carrying thread numbers and in the extension of

contact area on threads, which in turn leads to less deformation of the screw. The reason why the actual displacements in both ball and sliding screws exceed the calculated ones may be the existence of these various screw errors.

4. Discussion of Fine Feed Error

The actual fine feed was higher than the calculated value. Here, the difference between the actual and calculated values is discussed by classifying the displacement into the deformation components of the screw.

The screw deformation which produces the table fine feed consists of the thread deformation δ_T including Hertzian contact deformation in the case of the ball screw and the screw shaft deformation λ which is the sum of the screw shaft deformation at the mating portion of the nut and that at the spacing part. Let the displacement of nut 1 be δ_1 and that of nut 2 be δ_2 , then the following relationships hold between the displacements and deformations.

$$\left. \begin{aligned} \delta_1 &= \delta_T \\ \delta_2 &= \delta_T + \lambda \end{aligned} \right\} \quad (1)$$

Here, δ_T in the top equation is the deformation of screw shaft mating with nut 1, and δ_T in the bottom equation is that of nut 2.

δ_1 and δ_2 can be measured as the displacement of the table when it is connected to nut 1 and nut 2, respectively. It has been confirmed that the nut displacement coincides well with the table displacement. λ appears as the screw shaft deformation at the free side end. Therefore, δ_1 , δ_2 and λ are measured independently, and the differences between the measured and calculated values of δ_T and λ are discussed. At this point, in addition to the values measured directly, the indirect values are calculated from Eq. (1) which relates the displacement with the deformation.

The experiments are performed for both ball and sliding screws under the same initial preload of 700 N. The preload is increased up to 800 N and decreased to the initial value of 700 N with a preload change step of 25 N. During these experiments, there are no displacements of the screw shaft end at the fixed side.

Figure 4 shows the calculated λ , the measured λ' and the indirect values $\lambda' (= \delta_2' - \delta_1')$ obtained by subtracting the measured δ_1' from the measured δ_2' . The indirect values coincide well with the measured values, although they are gained independently. This means that there is no discrepancy between displacement measurement and measured values. The calculated value of screw shaft deformation λ of the ball screw is almost the same as that of the sliding screw due to the similar screw dimensions. The measured

Fig. 4 Deformation of screw shaft with preload change

Fig. 5 Thread deformation difference between measurement and calculation

values of the ball and sliding screws also appear the same. Consequently, the difference between the measured and calculated results of the ball screw coincides with that of the sliding screw. However, the measured values are about 1.5 times larger than the calculated values.

Figure 5 shows the difference $\Delta\delta_T (= \delta'_T - \delta_T)$ between the measured thread deformation $\delta_1 (= \delta'_T)$ and the calculated one $(= \delta_T)$, and the difference $\Delta\delta'_T (= \delta'_T - \delta_T)$ which is gained indirectly by subtracting the difference $(\lambda' - \lambda)$ between measured λ' and calculated λ from the difference between measured $\delta_2 (= \delta'_T + \lambda')$ and calculated $\delta_2 (= \delta_T + \lambda)$. Although these values of $\Delta\delta_T$ and $\Delta\delta'_T$ are gained from independently measured values, they agree well for each ball screw and sliding screw. $\Delta\delta_T$ and $\Delta\delta'_T$ correspond to the thread deformation on nut 1 and nut 2 sides, respectively. From the agreement between $\Delta\delta_T$ and $\Delta\delta'_T$, the thread deformations of nut 1 and nut 2 side are regarded to be identical.

A significant difference in thread deformation between the measurement and calculation appears in the ball screw compared with that of the sliding screw, as shown in Fig. 5. The thread deformation of the ball screw is essentially larger than that of the sliding screw because of Hertzian contact deformation. Accordingly, the influence of irregular thread contact due to the various screw errors may be large in the ball screw. For the ball screw, the ratio of the measured value to the calculated value is 1.46 which is almost the same as that of the screw shaft deformation. For the sliding screw, the measured value is six times as much as the calculated value. However, the calculated value of thread deformation for the sliding screw is very small, i.e., only one-thirtieth the screw shaft deformation. Thus, a slight error of measurement would magnify the ratio of the measured to calculated value.

According to the calculation, Hertzian contact deformation in thread deformation is the maximum, next is the screw shaft deformation and finally, the thread deformation without Hertzian contact deformation is the smallest. The differences between the result of measurement and calculation for each deformation follow this deformation order. The difference in thread deformation of the ball screw, in which Hertzian contact deformation makes up a major part of the deformation, reaches 70% of the total difference. Regarding the screw shaft deformation, the same degree of difference is obtained for both ball and sliding screws. The difference in thread deformation of the sliding screw without Hertzian contact deformation is the smallest.

5. Influence of Table Load

The frictional force of the table guideway may be one of the factors affecting the table fine feed. Thus, hydrostatic plain bearings are usually adopted as the table guideway for nanometer positioning equipment⁽³⁾. Under this circumstance, studies that deal with the table load effect on the fine feed have not been found, because the friction of hydrostatic guideway is very small. Here, the table is guided by the rolling elements. Although rolling friction is also small, the table load varies the frictional force. Thus it is uncertain whether the table load has an effect on the fine feed or not. Therefore, the fine feed property against the table load is examined by varying the table load, excluding the table mass (10.7 kg), from 10 to 40 kg. The maximum load of 40 kg is selected by considering the load carrying capacity of 37 kg on this feed unit. The table is connected to the free-side nut 2.

Figure 6 shows the table displacement when the

Fig. 6 Influence of table load on displacement

Fig. 7 Continuous table displacement

preload is stepped up and down in a total of four steps at each table load with the step amount of 5, 10, 15 and 20 N. These results are obtained with the ball screw under the initial preload of 700 N. The scattering of the displacements for the same preload change step is limited in a narrow range. Regardless of the table load, the table has the same fine feed with each preload change step.

Figure 7 shows the results for the sliding screw from which greater fine feed can be gained over that of the ball screw. The preload is varied over a wider range and a fine feed of 5 nm per preload change step of 2.5 N is obtained. Thus the sliding screw is superior in terms of fine feed resolution to the ball screw which shows a fine feed of 16 nm for the same preload change step as deduced from Fig. 6. Two sets of results obtained for only table mass (10.7 kg) and total mass of 50.7 kg are shown in Fig. 7. Following preload change, the table displacement occurs totally independent of the table load. The table displace-

ments at a preload change of 130 N for the total table mass of 10.7, 20.7, 30.7, 40.7 and 50.7 kg are 406, 409, 406, 408 and 403 nm, respectively. The mutual differences between these displacements are so small that they are considered accidental errors in the experiments.

In Fig. 7, there is a slight displacement difference between the loading and unloading period. This difference may be caused due to drift of the position sensor. If the displacement exhibits hysteresis phenomena, the displacement at unloading must be larger than that at loading. However, Fig. 7 shows the opposite result. Furthermore, the displacement after reversing to the initial preload becomes less than zero. This displacement after reversing to the initial preload sometimes becomes greater than zero, as shown in Fig. 10. These results suggest the difficulty of stable nanometer-order measurement of position over a long time owing to changes in environmental conditions such as temperature and/or the drift of the sensor.

In the case of the fine feed of nanometer order using the rolling contact elements, it is pointed out that there appears the nonlinear displacement accompanying hysteresis^{(2),(7)}. This phenomena is called nonlinear spring characteristics. In this feed unit, however, the fine feed accompanying the nonlinear spring characteristics is not observed.

6. Effectiveness of Fine Feed Control with Preload and Minimum Feed

Figure 8 gives the table displacements for the input voltage to the PZT. In this case, a ball screw is used and the table is connected to the free-side nut 2. The results for four input voltage ranges under two types of spacing part stiffness are shown in Fig. 8. The table displacements are classified into two groups in accordance with the spacing part stiffness. Moreover, the table displacements show hysteresis following the PZT characteristics. This hysteresis in the table displacement is significant for the higher spacing part stiffness and wider input voltage range. These results indicate that it is not suitable to utilize the input voltage for fine feed control. However, the fine feed gained by this method has a one-to-one correspondence with the preload change, as shown in Fig. 7.

On the other hand, the difficulty of stable measurement of nanometer-order positioning over a long period has been described. Figure 9 depicts two examples of the momentary change in the output of the capacitance-type position sensor used here and in the preload value while the preload is held constant. The output of the position sensor fluctuates by a few nanometers even if it appears to comparatively stable

Fig. 8 Table displacement with input voltage to PZT

Fig. 10 Table displacement with preload change

Fig. 9 Fluctuation of position sensor and preload

(on the top in Fig. 9) and sometimes varies irregularly by several tens of nanometers (on the bottom in Fig. 9). Meanwhile, the measured values of preload are stable within the fluctuation range of 1 N. The nominal resolving power of the capacitance-type position sensor is 1 nm. However, if the suitable environmental and measurement conditions are not available during the measurement, it may be difficult to maintain this high level of accuracy.

Consequently, if the preload is chosen as the control variable in stead of the input voltage to the

PZT based on the one-to-one correspondence between the preload and fine feed, then the fine feed can be controlled easily. Moreover, the preload will be effective for an indirect fine feed measuring sensor in a stable state.

Figure 10 shows the table displacement when the table is connected to the fixed-side nut 1 where more fine feed is gained compared with the connection case to the free-side nut 2. The preload change of 1 N corresponds to the fine feed of 4.5 nm for the ball screw and 1.1 nm for the sliding screw.

Figure 11 shows the table displacements measured by the position sensor and preload change for the ball screw. The table displacement and preload change are measured at the same time under the preload change step of 5, 2 and 1 N, which corresponds to 22.0, 9.0 and 4.5 nm step feed. In the figure of preload change, the displacements deduced from preload change are given simultaneously. The step feeds of 22.0 and 9.0 nm are detected by the position sensor, but it becomes difficult to detect the step feed of 4.5 nm. On the other hand, preload change of 1 N that corresponds to the step feed of 4.5 nm is detected.

Figure 12 shows the results for the sliding screw. The preload is changed in the same manner as for the ball screw, but in this case, the preload change step of 5, 2 and 1 N corresponds to 5.5, 2.2 and 1.1 nm step feed. The position sensor detects the step feed of 5.5 nm even where there is some fluctuation. From the results for both the ball and sliding screws, the limit of stable feed detection by the position sensor would be about 5 nm. The step feeds of 2.2 and 1.1 nm are not detected by the position sensor, as shown in Fig. 12. This result supports the unstable behavior of the position sensor output, as already shown in Fig. 9. Also a preload change of 1 N which corresponds to the step feed of 1.1 nm can be detected even if there exists

Fig. 11 Measured displacement and preload change, deduced displacement (Ball screw)

Fig. 12 Measured displacement and preload change, deduced displacement (Sliding screw)

some electric noise. Moreover, the measured preload change maintains reproducibility through the loading and unloading period. The detection until a 1 N preload change for both ball and sliding screws supports the preload variation of 1 N, as observed in Fig. 9.

It is necessary to determine whether the table actually displaces the step feed of 1 nm by using a more reliable sensor. However, the step feed of 5 nm

is detected directly by the capacitance-type position sensor. Furthermore, the step feed of 2 nm was also detected already in the previous study⁽⁵⁾ where the fine feed was performed by manual control of the input voltage to the PZT while observing the position sensor output. Thus, we consider that a 1 nm step feed has also been realized with this feed unit.

7. Conclusions

The basic characteristics of the fine feed in the proposed mechanism utilizing the preload change of the lead screw are examined, and the following results are obtained.

(1) The nonlinear deformation effect of the ball screw due to Hertzian contact on the fine feed can be ignored under an adequate initial preload and within the fine feed range of 1 μm .

(2) The differences between the calculated and experimental fine feeds are discussed by classifying them into the screw deformation components that are measured independent of each other. Both fine feed and components measured directly coincide well with those gained indirectly. The individual differences between measured and calculated components follow the order of the amount of each component.

(3) A table load up to 50.7 kg does not influence the fine feed in this feed unit. Moreover, the nonlinear spring characteristic effect on fine feed cannot be found during both the preload increase and decrease periods. The repeatability of the fine feed is also very good except the fluctuation caused by the drift in the output of the position sensor.

(4) The application of preload simplifies the fine feed control, and furthermore it is available as an indirect measuring sensor for the fine feed in place of the unstable position sensor in the nanometer region.

(5) The indirect measurement by preload change can detect the step feed of 5 nm which is the minimum value obtained by the capacitance-type position sensor used here.

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