A Study on Nanometer Positioning Table System Equipped with Electrorheological Fluid Units*

Hitoshi HASHIZUME** and Hidenori SHINNO**

With the increasing demands for higher accuracy and higher productivity in the manufacturing environment, ultraprecision table positioning technology of nanometer order is urgently required. In order to meet these requirements, it is necessary and indispensable to develop the ultraprecision table systems of noncontact type, which is constructed from an aerostatic guideway and a linear motor. However, such a table system of noncontact type has low performances in the positioning stability and the disturbance response, because of friction free and low damping capacity in the guideway. In this study, therefore, a linear motor-driven ultraprecision aerostatic table system equipped with electrorheological fluid (ERF) units has been developed. Furthermore, it has been verified that the developed ERF units are effective and applicable to simultaneously achieve quick-response and nanometer positioning accuracy.

Key Words: Positioning, Servo Mechanism, Accuracy, Electrorheological Fluid, Ultraprecision, Table System

1. Introduction

With the progress of ultraprecision machine tools and high density semiconductor equipments, the demands for higher speed and higher positioning accuracy of the table system are increasing steadily. It is necessary for such a table system to achieve smooth linear motion and accurate positioning, even though the table is affected by static, dynamic and thermal disturbances. Because the accuracy and productivity of manufacturing system depend largely on performances of the table system.

In general, a table system is constructed from a table, a guideway and a feed drive system. The characteristics of these fundamental components influence the overall performance of the table system as a whole. In order to simultaneously realize

nanometer positioning accuracy and high speed feed drive of a table, it is effective to minimize error factors and nonlinear characteristics in the table structure by using an aerostatic guideway of friction free and a linear motor of noncontact type⁽¹⁾. However, these structural configurations have also remarkable demerits, e.g., the low dynamic stiffness in the feed direction, the low positioning stability due to outer disturbances, the increase of settling time at high speed positioning, etc., because mechanical restriction does not exist in the objective table system.

In the recent research activities for solving such problems, some methods for improving the characteristics of a table system with the sliding mechanisms⁽²⁾, the electrorheological fluid (ERF) units⁽³⁾⁻⁽⁵⁾, the ferro magnetic fluid damper⁽⁶⁾ and the guide made of viscous-elastic material⁽⁷⁾ have been proposed. In particular, it is one of the most effective means for the linear motor-driven aerostatic table system of noncontact type to actively controlling the dynamic characteristics of the table using ERF.

Therefore, in order to establish future ultraprecision machine system, a nanometer positioning table system equipped with ERF units has been newly

* Received 16th September, 1999. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 65, No. 630, C (1999), p. 786-792 (Received 19th June, 1998)

** Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan. E-mail: hashizum@pi.titech.ac.jp

developed in this study. The developed system is driven by a brushless DC linear motor and guided by an aerostatic bearing⁽¹⁾. Furthermore, it has been verified that the developed ERF units are effective and applicable to simultaneously achieve quick-response and nanometer positioning capability.

2. Structural Configuration of the Nanometer Positioning Table System

Figure 1 and Table 1 show the structural configuration and the basic specifications of the developed table system equipped with ERF units, respectively. In order to simultaneously achieve nanometer positioning accuracy, high speed feed drive and positioning over long travel range of the table, an aerostatic guideway and a brushless DC linear motor have been used in this table system. The developed table system was designed as a simple and symmetrical configuration. And structural material for the table, the guideway and the base plate is alumina-ceramics (Al_2O_3) to materialize light weight, high stiffness and minimized thermal deformation. Through the structural configuration like this, the table is fundamentally supported by aerostatic bear-

ing made of porous material and driven by the linear motor in perfect noncontact condition, and therefore the system is free from nonlinear behavior such as stick-slip, backlash and other mechanical nonlinear phenomenon. As a result, static and dynamic characteristics of the table are only determined by the positioning control system, because the table system has no mechanical restriction. As clearly understood, a positioning error will occur directly by the disturbance force acting on the table in the direction of the feed drive. Therefore, a couple of ERF units has been installed of both sides of the table in parallel allocation, in order to actively control the characteristics of the table system. The developed ERF units are constructed of both a fixed electrode impounding ERF and an insulated moving electrode, as shown in Fig. 2.

Table 1 Basic specifications for the table system

Travel length	300 mm
Stiffness in vertical plane	600 N/ μm
Stiffness in horizontal plane	220 N/ μm
Mass of the table	19.6 kg
Maximum driving force	160 N
Maximum acceleration	6.4 m/s ²
Maximum velocity	320 mm/s

Fig. 2 Sectional view of an ERF unit

Fig. 1 Configuration of the table system using ERF

Fig. 3 Block diagram of the positioning control system

(a) Shear stress vs. electric field

(b) Shear stress vs. shear rate

Fig. 4 Characteristics of ERF

The effective area of the electrode is 0.032 m^2 , and the clearance of both electrodes is 1 mm . Using a couple of ERF units, the shear forces of ERF act on the table in the direction of the feed drive, and the characteristics of the table system can be actively controlled by adjusting the intensity of the applied electric field for ERF units. The colloidal ERF used in this study is mixture of carbon particles and non-conductive silicone oil.

Figure 3 shows the software PID control system with laser interferometer feedback for positioning the table. The resolution of the heterodyne laser interferometer used as a positioning sensor in this system is 0.63 nm ($\lambda/1024$), and the sampling frequency of the positioning control is 10 kHz . And also, the intensity of the applied electric field for ERF units is controlled

Fig. 5 Relationship between shear stress and shear strain

by the electric field controller according to the driving condition of the table.

3. Basic Characteristics of ERF

In the case of negligibly small disturbance, the resultant force acting on the table is only determined by the thrust force of the linear motor and the shear resistance of ERF. Therefore, the characteristics of ERF can be evaluated by the relationship between the thrust force of the linear motor and the motion of the table, and the thrust force of the linear motor is nearly equal to the shear force of ERF at constant feed rate of the table. Figure 4 shows mutual relationships among the intensity of the applied electric field, the shear rate and the shear stress. As clearly shown in Fig. 4(a), the shear stress of the ERF becomes higher in proportion to the applied electric field squared. And also, the shear stress of the ERF at lower shear rate becomes larger than that at higher shear rate, as shown in Fig. 4(b). The shear resistance of the ERF is negligibly small in comparison with the maximum thrust force of the linear motor (160 N) in absence of the applied electric field for ERF units, because the initial viscosity of the ERF is less than $23 \text{ mPa}\cdot\text{s}$. For instance, the shear resistance of the ERF at feed rate of 300 mm/s is less than 0.3 N in the absence of applied electric field.

Figure 5 shows the relationship between the shear stress and the shear strain of the ERF in the reciprocating motion of the table at constant shear rate.

Fig. 6 Relationship between shear stress and shear strain in the region of micro shear strain

As shown in this figure, the shear stress becomes higher with the increase of shear strain in the region from the beginning point of feed drive motion to the shear strain of 1, then the shear stress becomes constant with shear strain passing over 1. And also, the shear stress briefly decreases when the direction of feed motion is turned over, then the shear stress becomes constant with the increase of shear strain from turnover of feed motion passing over 1. These stress-strain curve shows that the particulate chains in ERF deforms with the increase of shear strain in the region of small shear strain, i.e., the shear stress of ERF depends on elastic deformation of the particulate chains. On the other hand, in the region of large shear strain, disintegration and reintegration of the particulate chains occur. In particular, in the region of micro shear strain, the slope of the stress-strain curve becomes larger with the increase of applied electric field, i.e., the static stiffness of the table system becomes higher by shear stress of ERF. Figure 6 shows the relationships between the shear stress and the shear strain in the region of micro shear strain. As is clear by shown in this figure, the relationships between both the shear stress and the shear strain can be indicated by a hysteresis curve. The slope of the ellipse axis and the area of the hysteresis loop become larger with the increase of the applied electric field and the shear strain. The slope of the ellipse axis K shown in Fig. 6 corresponds to the stiffness of the

Fig. 7 Effect of shear strain on stiffness of hysteresis loop

Fig. 8 Effect of shear strain on energy loss of hysteresis loop

table, and the area of the hysteresis loop corresponds to the energy loss. Figures 7 and 8 show the relationships among the stiffness, the energy loss, the intensity of the applied electric field and the shear strain. As shown in these figures, the stiffness becomes higher with the decrease of the shear strain, but the energy loss becomes lower with the decrease of shear strain. From these results, it can be ascertained that the developed ERF units are effective and applicable to improve static stiffness and damping capacity of the table in perfect noncontact condition.

4. Evaluations of Disturbance Response

4.1 Disturbance response of the table in stopping mode

The developed nanometer positioning table system is driven by a brushless DC linear motor and guided by an aerostatic bearing in perfect noncontact condition. Thus, a positioning error will be caused due to the disturbance force acting on the table if the ERF units are not installed, because mechanical restriction in the direction of the feed drive does not exist in the table system. The some disturbance responses of the table were evaluated at adjusted intensity of the applied electric field for the ERF units. Figure 9 shows the disturbance response of the table in stopping mode, while adding sine wave signal in the force command F_{ref} to the linear motor as shown in the block diagram of Fig. 3. The amplitude of the

Fig. 9 Actual disturbance response of the table

Fig. 10 Simulated disturbance response of the table

disturbance force is 1 N. As shown in Fig. 9, the displacement deviation of $0.3 \mu\text{m}$ can be observed at the resonance frequency about 60 Hz without the applied electric field to ERF. And also, this figure shows that the maximum position error becomes lower with the increase of the applied electric field, i.e., the disturbance response of the table system can be improved by applying the electric field to ERF. Figure 10 shows the simulated disturbance response of the table, in which the simulated disturbance response can be calculated by estimating the static stiffness K at displacement of $0.3 \mu\text{m}$ as shown in Fig. 7. As clearly compared Fig. 9 with Fig. 10, the simulated disturbance response was in agreement with the actual disturbance response, i.e., the particulate chains of ERF behave like an elastic body in the region of micro shear strain. As a result, a spring effect of ERF becomes dominant in the micro displacement region.

Figure 11 shows the disturbance response of the table for an impulse force in the direction of the feed drive. The impulse force is affected by adding impulse signal equivalent to 5 N in the force command F_{ref} for the linear motor, as shown in Fig. 3. Figure 11 shows that the displacement deviation of the table is rapidly stabilized to zero by applying electric field to ERF. Figure 12 shows the 2 nm stepwise positioning of the table. This figure shows that a clear 2 nm stepwise positioning can be achieved by adjusting the electric field of ERF units. As mentioned above, performances

(a) $E = 0.0 \text{ kV/mm}$ (b) $E = 2.4 \text{ kV/mm}$

Fig. 11 Response of the table for impulse force

(a) $E = 0.0 \text{ kV/mm}$ (b) $E = 2.4 \text{ kV/mm}$

Fig. 12 2 nm stepwise response of the table

of the developed ultraprecision positioning table system can be largely improved by applying the electric field to ERF.

Fig. 13 Disturbance response of the table while feeding

4.2 Disturbance response of the table in moving mode

Figure 13 shows the disturbance response of the table in moving mode. The disturbance force is affected by adding sine wave signal in the force command F_{ref} for the linear motor as shown in the block diagram of Fig. 3. In this case, the amplitude of the disturbance force is 1 N. As shown in Fig. 13, the disturbance response of the table can be improved by ERF effect at low feed rate of 10 mm/s (shear rate 10 s^{-1}), however, the improvement can not be observed at high feed rate of 100 mm/s (shear rate 100 s^{-1}). Thus, these facts show that the shear force of ERF takes certain effect on the table as resistive force according to the table speed during driving at the constant speed as shown in Fig. 4. On the other hand, the ERF has ineffective on restraining the micro vibration. Because the mechanism to produce shear stress of

ERF in table moving mode is different from the case that the table is in stopping mode. This result can be also assumed that the variation of shear rate due to the vibration of the table is comparatively small because of the large clearance of both electrodes in the developed ERF units.

5. Conclusions

In order to simultaneously achieve higher accuracy and higher speed feed drive of nanometer positioning table system, a brushless linear motor-driven ultraprecision aerostatic table system equipped with ERF has been developed. Furthermore, the characteristics of ERF in the region of micro shear strain have been clarified, and the relationships between the characteristics of ERF and the positioning performance of the ultraprecision table system have been investigated. As a result, the following conclusions can be drawn from this study.

(1) In table stopping mode, the relationships between the shear stress and the shear strain of ERF can be expressed by a hysteresis curve, which depends on both the applied electric field and the shear strain of ERF. And the slope of an ellipse axis which corresponds to static stiffness becomes higher with the decrease of the shear strain and the increase of the applied electric field, but the area of a hysteresis loop which corresponds to the energy loss becomes lower with the decrease of the shear strain.

(2) The disturbance response of the table can be improved by adjusting the applied electric field of ERF units in table stopping mode. In particular, the particulate chains of ERF behave like an elastic body which has stiffness according to both the intensity of the applied electric field and the shear strain in the region of micro shear strain.

(3) The displacement deviation of the table due to the floor vibration decreases with applied the electric field of ERF units, i.e., static and dynamic characteristics of the table system can be actively controlled by adjusting the applied electric field of the ERF units, which is clearly also manifested the 2 nm stepwise positioning.

(4) Shear stress of ERF takes effect on the table as resistive force depending on the intensity of the applied electric field and the shear rate in table moving mode. However, the restraining function of micro vibration by ERF becomes ineffective with the increase of the feed rate of the table.

Acknowledgement

This research project has been carried out under the financial support of the Scientific Research Fund from the Ministry of Education, Grant-in-Aid for

Scientific Research (A) (1) No. 08555033.

References

- (1) Hashizume, H. and Shinno, H., Development of High Speed Nanometer Positioning Table System and Its Performances Evaluation, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 64, No. 626, C (1998), p. 4103-4108.
- (2) Baumgartner, H., Gedämpfte Längsführungen mit Wälz-körpern, *Werkstatt und Betrieb*, Vol. 110, No. 8 (1977), p. 529-531.
- (3) Hashizume, H., Shinno, H., Ito, Y. and Sato, C., Characteristic Control of Table System Using Electrorheological Fluid (Comparison of Colloidal ERF with Liquid Crystal), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 61, No. 590, C (1995), p. 4105-4110.
- (4) Ishiyama, M., Aoyama, T. and Edamura, K., Application of Electrorheological Fluid for Dynamic Performance Enhancement of Machine Tool Table Systems (Analysis of the Dynamic Characteristics of a Simple Table System), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 60, No. 577, C (1994), p. 2964-2970.
- (5) Ishiyama, M., Aoyama, T., Edamura, K. and Tsuzuki, Y., Application of Electrorheological Fluid for Dynamic Performance Enhancement of Machine Tool Table Systems (Trial Manufacture of a Table System and Performance Evaluation by Means of Cutting Tests), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 593, C (1996), p. 362-332.
- (6) Higashimoto, A., Watanabe, T., Kakino, Y., Li, Z., Nakano, Y. and Maruyama, H., The Study of Improvement on Dynamic Characteristics of Position Control System by Viscous Controllable Fluid Damper (1st Report, Improvement of Dynamic Characteristics of Ball Screw Driving Mechanism by Auxiliary Mass Viscous Damper with Ferro Magnetic Fluid), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 64, No. 618, C (1998), p. 683-689.
- (7) Numasato, H. and Kobayashi, I., Optimizing Mechanical Damping Factor and Improvement of the Positioning Control Performance Using Viscous-Elastic Guide, *J. Jpn. Soc. Prec. Eng.*, (in Japanese), Vol. 60, No. 2 (1994), p. 206-210.