euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017
www.euspen.eu

Microscopic behaviour of ultraprecision positioning mechanism driven by ball screw with external axial load

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Abstract

To clarify ultraprecision positioning performance of a ball screw under more practical conditions with external axial load, microscopic behaviour of a preloaded ball screw is here considered experimentally under loaded conditions. Experimental apparatus is devised to apply axial load to the ball screw by using a voice-coil-type actuator. The relation between the motor torque and the displacement shows nonlinear elastic behaviour with hysteresis; the relation between the rotational angle and the nut displacement maintains linearity based on the lead of screw still in loaded condition. It is thus shown that the median value of the motor torque shifts with an increase in the axial load, and effect of the axial load is discussed from the viewpoint of energy balance.

Keywords: Ultra-precision positioning, Ball screw, Nonlinear elastic property, Axial load, Linear actuator

1. Introduction

Positioning mechanisms driven by preloaded ball screws show nonlinear elastic behaviour within a range of several micrometres. In previous reports, various experiments were performed to clarify the microscopic behaviour of ball screws, and a mechanical model for the nonlinear property was proposed [1]. In addition, ultraprecision positioning with sub-nanometre level resolution was realized by adapting a control system matching the nonlinear elastic property [2]. However, those results were obtained under conditions without any external axial load. The microscopic behaviour of simple friction phenomenon has been discussed and modelled in many ways [3]. However, unlike bearings, ball screws having lead angle do effective work against external axial load, so that effect of the external load on the microscopic behaviour is not obvious. Thus, in this report, microscopic behaviour of the preloaded ball screw is considered experimentally under various loaded conditions.

2. Experimental apparatus

Figure 1 shows the experimental apparatus. A preloaded ball screw with a lead of 5 mm drives the stage, supported by an aerostatic guide way with stroke of 100 mm. The preload is then applied using oversized balls, and the equivalent axial preload is 490 N. A DC servomotor of 130 W rotates the screw shaft, and the nut moves in the axial direction. To apply axial load to the stage, an electromagnetic linear actuator using a voice coil motor was newly designed and produced. Its force to current ratio was 50 N/A.

Definitions of experimental variables are shown in Figure 2. A linear encoder with resolution of 0.069 nm measures the stage displacement, and an optical rotary encoder measures the rotational angle with a resolution of 1.75 μrad. The motor current I is monitored at all times, and the motor torque T is derived by multiplying the current by the torque constant of the motor.

3. Experimental results

The microscopic motions of the ball screw mechanism are measured using small sinusoidal position commands x_r in Fig. 2 with stationary axial load. Figure 3 shows an example of the experimental results where the amplitude of displacement x_0 is 3 μm under no axial load. The cyclic period of sinusoidal input is 10 sec, and the rotational angle and displacement follow the torque change, so the elastic property can be simply shown. Figure 4 shows the relation between motor torque T and displacement x with axial load F. In case of x_0=30 μm, the amount of T is saturated with maximum value of 0.1 Nm, so

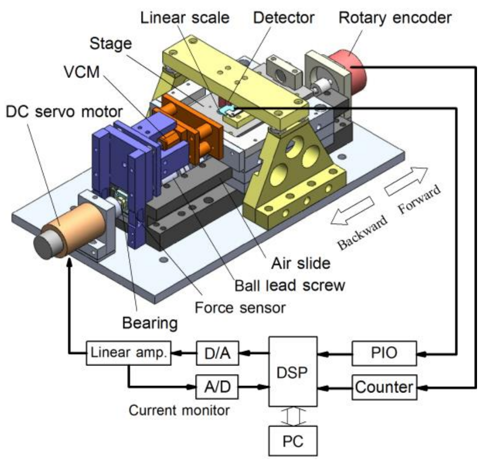


Figure 1 Experimental apparatus

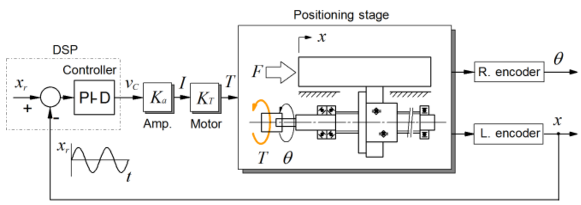


Figure 2 Experimental variables

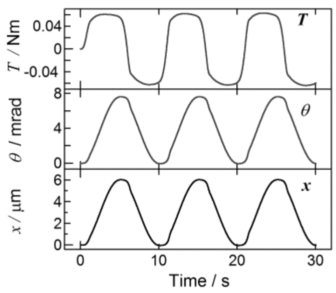
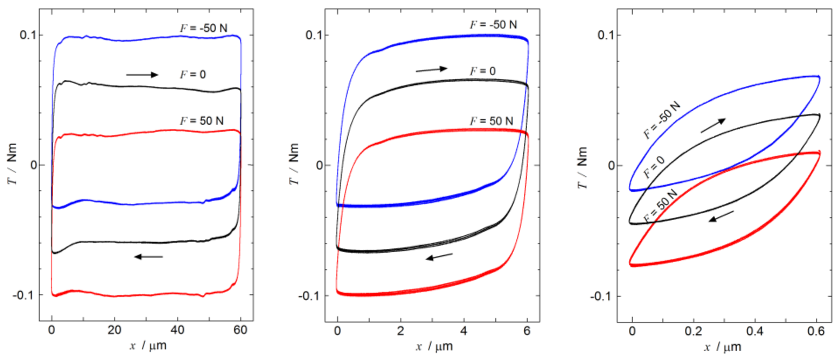
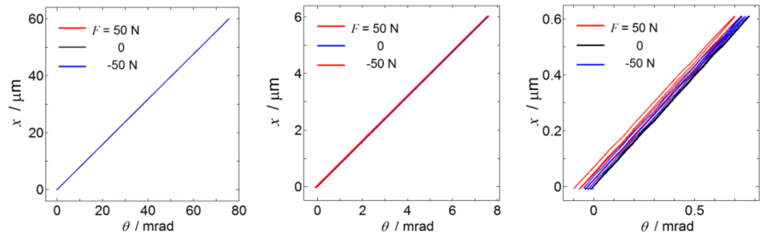


Figure 3 Time domain response



(a) x_0=30 μm (b) x_0=3 μm (c) x_0=0.3 μm

Figure 4 Relation between motor torque T and displacement x



(a) x_0=30 μm (b) x_0=3 μm (c) x_0=0.3 μm

Figure 5 Relation between displacement x and rotational angle θ

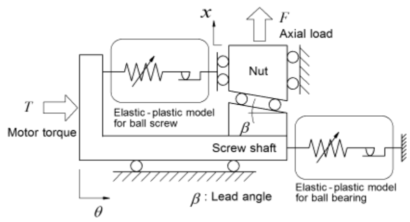


Figure 6 Mechanical model

that the friction between the screw shaft and the nut is governed by the macroscopic rolling friction. It is also shown that the median value of the motor torque shifts with an increase in the axial load. When the x_0 becomes less than 3 μm, the relation between T and x shows nonlinear elastic behaviour with hysteresis. However, the configuration of the hysteresis does not change with the axial load. In those cases, though the median value of T also shifts with an increase in the axial load, the amount of the shift becomes smaller as x_0 decreases. On the other hand, Figure 5 shows the relation between the rotational angle θ and x: That relation maintains linearity based on the lead of the screw still in loaded condition.

4. Discussion

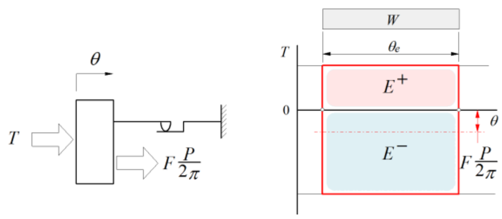
Figure 6 shows the mechanical model for the microscopic behaviour of the ball screw mechanism with support bearing. Because the relation between x and θ maintains linearity with lead angle β, the model with axial load F is simplified as in Figure 7 with the lead P of the screw. In the case with only Coulomb's friction, as shown in (a), the median value of T shifts with the axial load, and the work of motor torque E+ in forward motion and E- in backward motion maintain following relation while moving around the T-θ curve.

$$\left(E^{+}+W\right)+\left(E^{-}-W\right)=L \tag{1}$$

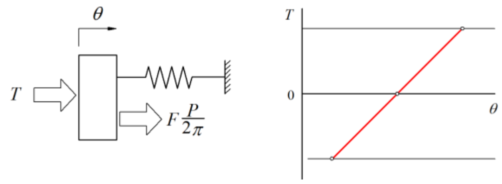
where W is the magnitude of the work of axial load, and L is dissipation energy in one round shown by the area of the rectangle. If the total loss L is composed of L+ and L- as follows,

$$\left.\begin{aligned} L^{+}&=E^{+}+W \\ L^{-}&=E^{-}-W \\ L^{+}&=L^{-} \end{aligned}\right\}, \text{then } E^{-}-E^{+}=2W \tag{2}$$

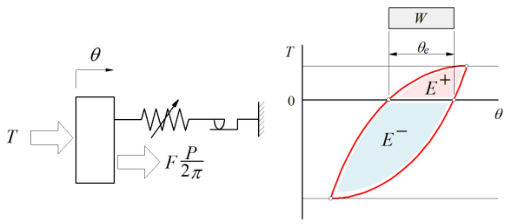
The amount of shift of the median value of T is determined by eq. (2). In a case with a simple elastic element, as shown in (b), the axial load only exchanges work with the elastic potential of the spring: It does not show the shift of T-θ curve. With the combination of Coulomb's friction and an elastic element, as shown in (c), the shift of the T-θ curve is also explained by eq. (2). When the amplitude of rotation decreases, the θ_e in the hysteresis curve also decreases, which means W in eq. (2) becomes smaller. Subsequently, the shift of the hysteresis curve decreases.



(a) Coulomb's friction



(b) Simple elastic property



(c) Nonlinear elastic property

Figure 7 Property of nonlinear elastic behavior

5. Conclusions

Microscopic behaviour of the preloaded ball screw is here considered under externally loaded conditions. Microscopic behaviour can be explained by using the mechanical model proposed in previous reports: The effect of external load on the shift of the elastic hysteresis curve is determined by the energy balance between the work of axial load and motor torque, the friction loss and the elastic potential.

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