Ultraprecision positioning with sub-nanometer resolution by using ball screw and aerostatic guide way

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Abstract

An experimental positioning system is constructed using a ball screw, an aerostatic guide way and a laser hologram linear encoder, to investigate performance of the ball screw mechanism in the sub-nanometer range. The experimental results prove that the final settling of positioning is ruled by the microscopic elastic property, and that the positioning system has an ultra-fine resolution at sub-nanometer level.

1 Introduction

Leadscrews are widely used in manufacturing systems aiming at high-precision positioning over various lengths of stroke from several dozen millimetres up to several meters. There are various kinds of leadscrews - sliding type, rolling type and hydrostatic or aerostatic type - and ball screws are mostly used in practical applications [1)]. Recently the resolution of a linear encoder applying laser hologram has greatly improved: The performance achieves ultrafine resolution in pico-meters (pm): Accordingly, the mechanism using the ball screw is expected to result in positioning performance with sub-nanometer level resolution. This study aims at making possible ultraprecision positioning with sub-nanometer level resolution using a ball screw mechanism

2 Experimental apparatus

Figure 1 shows the experimental apparatus newly developed in order to determine microscopic behavior

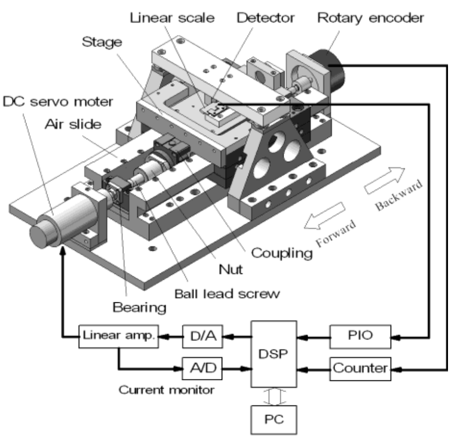
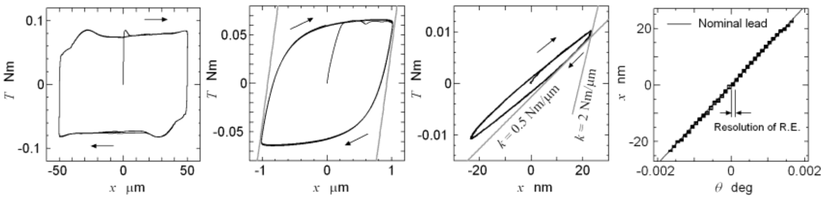


Figure 1: Experimental apparatus



(a) T-x relation (b) x-θ relation

Figure 2: Microscopic behavior of mechanism

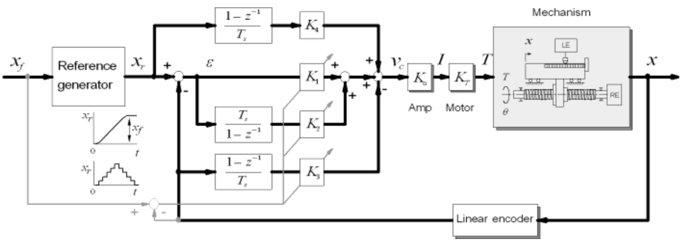


Figure 3: Block diagram of control system

in the sub-nanometer range. A preloaded ball screw with a lead of 5 mm and a shaft diameter of 20 mm drives the stage supported by an aerostatic guide way. The air slide is made of alumina ceramics, and has a stroke of 200 mm. A DC servomotor of 130 W rotates the screw shaft, and the nut moves in the axial direction. The nut is coupled to the stage by a special flexible device, with four degrees of freedom, which eliminates excessive constraint between the nut and the stage. A linear encoder with resolution of 69 pm measures stage displacement, and an optical rotary encoder measures the rotational angle with resolution of 0.0001 deg.

3 Microscopic property of mechanism

First, the microscopic property of the ball screw mechanism is measured using a small sinusoidal current input to the motor. Figure 2 shows the experimental results. The mechanism behaves macroscopically, over a stroke of 10 microns, as a free inertial body with constant friction, but, in the microscopic range within several microns, the relations between the motor torque T (=$K_T \cdot I$, K_T: torque constant of the motor, I : motor current) and stage displacement x show nonlinear elastic behavior with hysteresis: This elastic behavior is the result of the ball screw and the ball bearings supporting the screw shaft [2) 3)]. The hysteresis loop of T-x relation in the stroke of 20 nm is characterized by two spring constants, 0.5 Nm/micron and 2

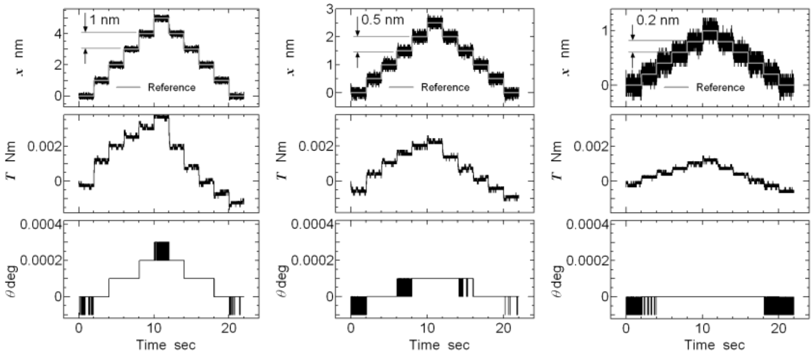


Figure 4: Micro step positioning

Nm/micron. In contrast, the relation between stage displacement x and rotational angle θ remains linear in these microscopic ranges, as shown in Fig. 2(b). Therefore, the controlled mechanism changes into a mass-spring system within microscopic range, and a feature which should be considered in control system design [4)].

4 Positioning performance

4.1 Control system

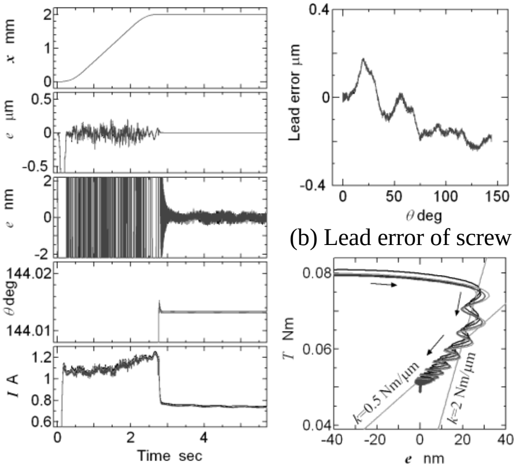
Figure 3 shows the control system. The controlled system is type 1 in case of reference displacement input over the macroscopic range, but it becomes type 0 in the microscopic range, because of the nonlinear elastic property present in microscopic range. Thus, the control system needs a compensator for velocity in macroscopic motion, and it needs an integral control action in microscopic range to keep the steady state error zero. A three-degrees-of-freedom control system with feedback and feedforward compensators is realized by using a digital signal processor with sampling rate of 8 kHz.

4.2 Micro-step positioning

Figure 4 shows experimental results of micro-step positioning. In case of 1 nm step, the displacement x shows a clear stepwise response, while the fluctuation becomes prominent as the step is decreased to sub-nanometers, and the positioning resolution reaches a limit at 0.2 nm. The figure also shows transitions of motor torque T and rotational angle θ: The transition of motor torque follows the change of reference positions. Because the mechanism is under an elastic condition in these microscopic ranges, the operating resolution of motor current limits the positioning resolution. The observation of rotational angle is limited in rough configuration because of insufficient resolution of the rotary encoder.

4.3 PTP positioning

In PTP (point to point) positioning, the stage is forced to follow a smooth reference trajectory of displacement derived from the sinusoidal acceleration curve. Figure 5 shows results of 2 mm step positioning repeated five times, with all results superposed on the figure. Figure 5(c) shows *T-x* relation around the settling point. It is proved that the final settling of positioning is ruled by the microscopic elastic property with the same spring constants as shown in Fig. 2(a). Figure 6 is a histogram of positioned deviation repeated 20 times under the same conditions. It shows that the controlled bias error is less than 0.1 nm, with standard deviation of positioning repeatability less than 0.2 nm. Therefore, sub-nanometer positioning is accomplished by using the ball screw.



(a) Time domain response

(b) Lead error of screw

(c) *T-x* relation around settling point

Figure 5: PTP positioning of 2 mm step

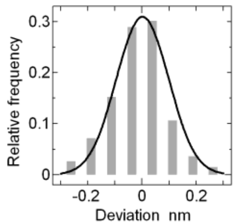


Figure 6: Histogram of positioned deviation

5 Conclusion

Positioning performance of the ball screw mechanism is investigated experimentally in the sub-nanometer range using the experimental positioning system. It is demonstrated that the positioning performance in sub-nanometer range is ruled by the microscopic elastic property of rolling elements.

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