Ultra-precise Positioning over a One-millimeter Stroke by Using a Coaxial Differential Ball Screw

S. Fukada[1], S. Motohashi[2], Y. Tamura[2], A. Miyashima[1], H. Sato[1]
[1] *Shinshu University, Japan*
[2] *NIDEC TOSOK Co., Japan*

sfukada@shinshu-u.ac.jp

Abstract

A new type of ‘coaxial differential ball screw’ (CDBS) is proposed, and some experiments are performed to evaluate the performance of the mechanism driven by a step motor. After devising a simple error compensation algorithm, the travel deviation decreased to less than 0.4 microns with a positioning resolution of 5 nm.

1 Introduction

Current precise positioning mechanisms can be divided into two categories based on the field of application: mechanisms with a long stroke, from millimeters up to meters, used in machine tools or semiconductor manufacturing processes; and fine mechanisms with a stroke measured in micrometers, used in scanning probe microscopes [1][2]. This study aims at realizing a simple positioning mechanism with nanometer level resolution over a one-millimeter stroke using a differential ball screw: a mechanism to fit in the medium range between the above two categories. In our previous report, a series-type differential ball screw, with two different leads on a screw shaft in series, was constructed [3]. However, that mechanism had a longer configuration than standard ball screw mechanisms, so in this report, a new type ‘coaxial differential ball screw’ is proposed to solve the problem.

2 Structure and principle

Figure 1 shows a mechanism using a coaxial differential ball screw, which consists of three major elements: an input screw, an output screw and a nut. The input screw is cylindrical, and has both an outer screw thread and or internal screw thread for the ball screw operation. The outer

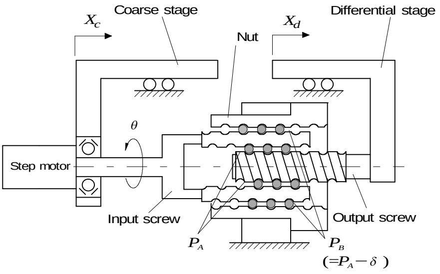


Figure 1: Principle of positioning mechanism using CDBS

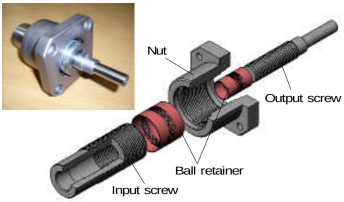


Figure 2: Coaxial differential ball screw

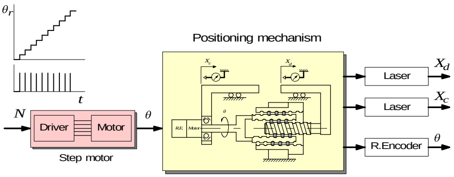


Figure 3: Experimental positioning system

screw thread meets the internal screw thread of the nut, and the internal screw thread meets the output screw. Thus, the mechanism contains two parts of the ball screw, A and B in the coaxial overlapped condition, and their nominal leads are P_A and P_B. Displacements X_c and X_d are nominally determined by eq. (1) as a function of the rotational angle θ of the screw shaft:

$$X_c = \frac{P_B}{2\pi}\cdot\theta \quad , \qquad X_d = \frac{(P_A - P_B)}{2\pi}\cdot\theta = \frac{\delta}{2\pi}\cdot\theta \qquad (1)$$

where δ is 'differential lead'. Figure 2 shows the structure of a manufactured CDBS. The input screw has an outer diameter of 31.5 mm, and the output screw has an outer diameter of 16 mm. The nominal leads are P_A=2.00 mm and P_B=1.9 mm, so the resultant differential lead δ is 0.1 mm.

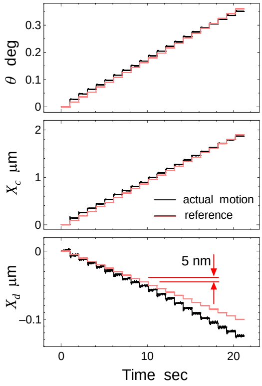
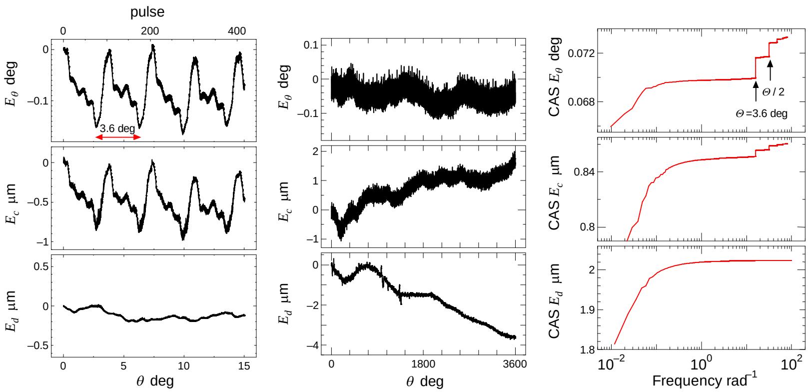


Figure 4: Positioning resolution

3 Positioning performance

3.1 Positioning resolution

A positioning system was constructed as shown in Figure 3 using the coaxial differential ball screw driven by a step motor with 5 phases. Though the critical step angle of the motor is 0.72 deg, the operating step angle is adjustable in the range between 0.00288 deg and 0.72 deg. The displacement of the coarse stage, X_c, and differential stage, X_d, are measured by a laser interferometer with resolution of a 1.2 nm, while the actual rotation angle of the step motor is measured by a rotary encoder with resolution of 720,000 ppr. The feed characteristics and positioning performance were measured in detail. Figure 4 shows positioning resolution of the mechanism when the step angle of the motor is set for 0.018 deg: It was found that the mechanism had a fine positioning resolution of 5 nm.



(a) θ_0=15 deg (b) θ_0=3600 deg (c) CAS for full stroke

Figure 5: Feed error

3.2 Feed error

Next, feed error of the mechanism is measured. Figure 5 shows the measured results when reference rotation angles θ_0 are (a) 15 deg and (b) 3600 deg (full stroke). E_θ, E_c and E_d are rotational angle error of the motor, travel error of the coarse stage and travel error of the differential stage respectively. The errors are defined as follows,

$$E_\theta = \theta - \theta_r, \qquad E_c = X_c - \frac{P_B}{2\pi}\theta_r, \qquad E_d = X_d - \frac{\delta}{2\pi}\theta_r \tag{2}$$

where θ_r is reference of rotational angle, and θ is the actual rotational angle of the motor. Figure 5(a) shows that E_θ and E_c include a prominent cyclic error with a period of 3.6 deg, which corresponds to the pitch of teeth around the rotor of the motor; the cyclic error is not included in E_d. Figure 5(c) shows the cumulative amplitude spectrum of (b). It also shows that E_θ and E_c have an error source with a period of 3.6 deg, while E_d shows a smooth change without any significant components. These results mean that the simultaneous differential effect negates the synchronous errors in screw-A and screw-B.

3.3 Repeatability and error compensation

As shown in Figure 5(b), the mean travel deviation is 4 microns over the total length of the stroke, with a fluctuation less than 0.2 microns. Figure 6 shows repeatability of the travel error for 20 times repetition. E_{dm} represents the average of the travel error, and σ_d is standard deviation at each position. Though the value of the mean travel deviation is significant, the travel error shows satisfying repeatability with a standard deviation of 0.1 microns. Therefore, real-time error compensation is

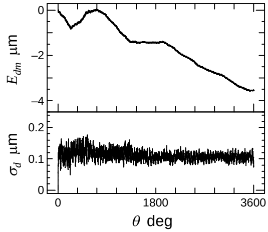


Figure 6: Repeatability

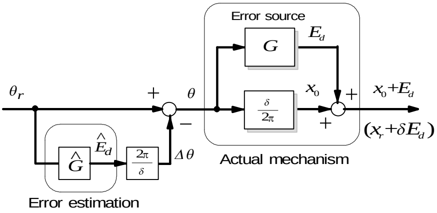
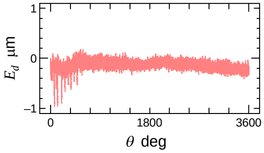
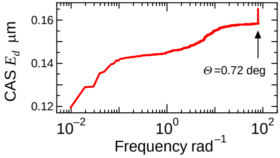


Figure 7: Error compensation method

available. A simple error compensation algorithm, as shown in figure 7, was devised and applied to this positioning system. The travel error of the actual mechanism was measured beforehand, and an error estimation model was installed in the controller. The reference rotation angle of the motor was modified to eliminate the estimated error at every interval of 0.72 deg for 20 command pulses to the motor. Figure 8 shows the travel accuracy with real-time compensation: Travel deviation decreased to less than 0.4 microns over the total length of the stroke, and the final value of CAS is 0.16 microns, which approximately corresponds to the value of ±2σ_d in figure 6.



(a) Travel error



(b) CAS

Figure 8: Travel accuracy with compensation

4 Conclusion

A new type of coaxial differential ball screw was devised, and a positioning mechanism constructed, to consider positioning performance of the differential ball screw. It was verified experimentally that ultra-precise positioning can be realized by CDBS with a travel deviation of less than 0.4 microns and with a fine positioning resolution of 5 nm. On the basis of the above experimental results, the potential of the positioning mechanism using coaxial differential ball screw is confirmed.

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