Linear stepping actuator with ultra-fine resolution using coaxial differential ball screw

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Keywords: ball screw, differential screw, linear actuator, nanometer resolution

Abstract

A new type linear actuator with nanometer level resolution is proposed by integrating a ‘coaxial differential ball screw’ (CDBS) with a stepping motor into a compact unit. The performance of the developed actuator is here evaluated experimentally. After devising a simple error compensation algorithm, the travel deviation is reduced to less than 0.06 microns (RMS) with positioning resolution of 5 nm.

1. Introduction

Current actuators used for precision positioning can be divided into two categories based on field of application: actuators with a long stroke, from millimeters up to meters; and fine actuators with a stroke measured in micrometers. For the latter, piezo actuators are generally used to enable nanometric resolution, but the piezo stroke is limited to a few dozen micrometers [1]. This study aims at realizing a simple actuator with nanometer level resolution over a one-millimeter stroke by using a differential ball screw, an actuator for the medium range between the above two categories. In our previous report, a new type ‘coaxial differential ball screw’ was proposed, and superior performance of the mechanism was shown [2]. In this report, the coaxial differential ball screw is integrated with a stepping motor to realize a compact linear stepping actuator with ultra-fine resolution over a one-millimeter stroke, and the performance of the actuator is evaluated experimentally.

2. Principle and structure

Figure 1 shows the principle of a developed linear actuator using a coaxial differential ball screw (CDBS). The actuator has three

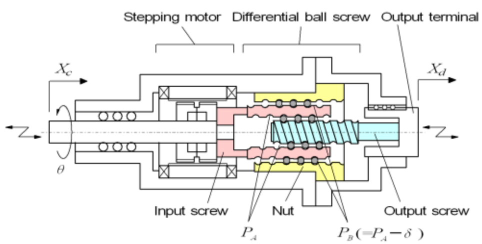


Figure 1: Principle of linear actuator using CDBS

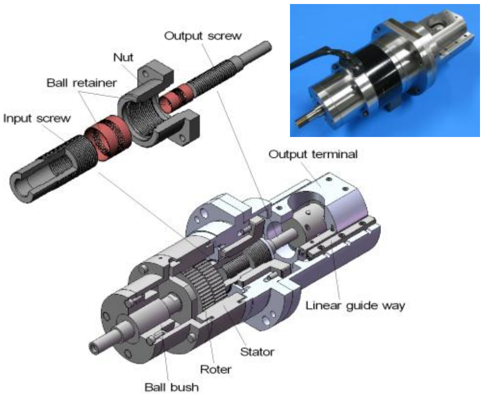


Figure 2: Linear stepping actuator using CDBS

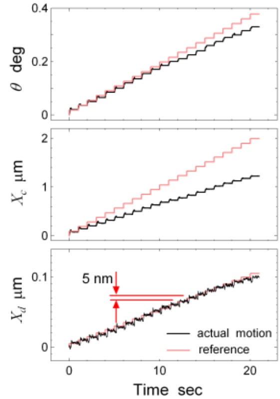


Figure 3: Positioning resolution

parts: a CDBS mechanism, a stepping motor and an output terminal. The CDBS consists of three major elements: an input screw, an output screw and a nut. The mechanism contains two ball screws, A and B in coaxial overlapped condition, and their nominal leads are P_A and P_B. Displacements X_c and X_d are nominally determined as in eq. (1) as a function of rotational angle θ of the input screw:

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

where δ is differential lead. Figure 2 shows the structure of a developed linear actuator. The lead P_A is 2.0 mm, P_B is 1.9 mm, and the resultant differential lead δ is 100 microns. The input shaft of the CDBS forms a rotor surrounded by stator coils of stepping motor with basic resolution of 0.72 deg. The basic stepping angle can be divided electrically into 500 parts, and the resultant resolution of the motor is 125 kppr at most: The resolution of the linear actuator reaches 0.8 nm theoretically.

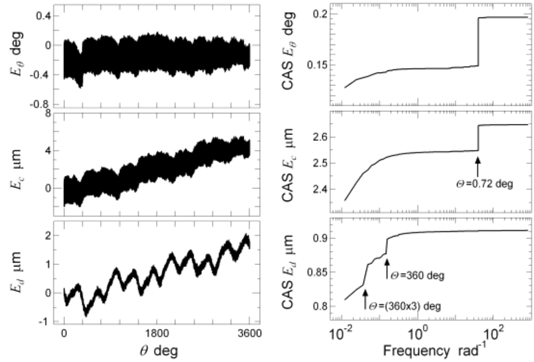
3. Positioning performance

3.1 Resolution

To evaluate the linear stepping actuator, an experimental apparatus was constructed: The displacement of the output terminal of the actuator was measured by a spectral-interference laser displacement sensor with resolution of 1 nm. The displacement of the input screw was measured by a laser interferometer, while the actual rotation angle of the input screw was measured by a rotary encoder with resolution of 720 kppr. Response of the output terminal to stepwise input was measured, and Figure 3 shows positioning resolution of the mechanism when the step angle of the motor is set for 0.018 deg: It is confirmed that the actuator has a fine resolution of 5 nm.

3.2 Feed error

Next, feed error of the linear motion was measured. Figure 4 shows the measured results when reference rotation angle θ_0 is 3600 deg (full stroke of 10 rotations). E_θ, E_c and E_d represent: rotational angle error of the motor, travel error of the input screw and travel error of the output terminal, respectively. The errors are defined as follows:



(a) Fluctuation of errors (b) CAS for full stroke

Figure 4: Feed error

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

where θ_r is reference of rotational angle, and θ is the actual rotational angle of the motor. Figure 4(a) shows that E_θ and E_c include prominent fluctuations with high frequency. Figure 4(b) shows the cumulative amplitude spectrum (CAS) of (a). It also shows that E_θ and E_c have an error source with a period of 0.72 deg, which corresponds to the basic resolution of the motor. On the other hand, the cyclic error with such high frequency is not included in E_d. These results show that the simultaneous differential effect negates the synchronous errors in screw-A and screw-B. E_d is affected by cyclic error components with a rather long period of one rotation (360 deg), or three rotations. The component of three rotations is caused by the lead (6 mm) of the master leadscrew of the thread grinder that finished the screw grooves.

3.3 Repeatability and error compensation

Figure 4 shows that the mean travel deviation reaches 2 microns over the total length of the stroke, and RMS value of the travel deviation is 0.91 microns, derived from the final value of CAS. Figure 5 shows repeatability of the travel error for 20 times repetition. $\overline{E}_d$ 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 consistent repeatability with standard deviation less than 0.1

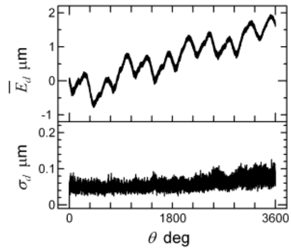


Figure 5: Repeatability

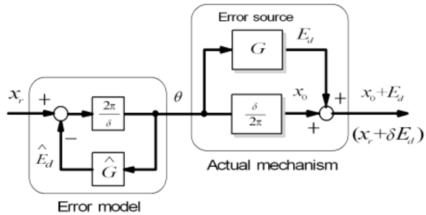
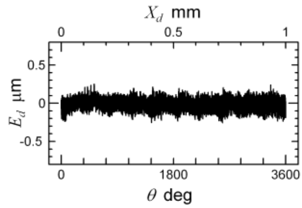
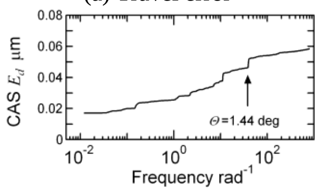


Figure 6: Error compensation method

microns, so error compensation is available. A simple error compensation algorithm, as shown in Figure 6, was devised and applied to this actuation system. The travel error of the actuator has been measured beforehand, and then error estimation model is installed in the controller. The reference rotation angle of the motor is modified to eliminate the estimated error at every interval of 0.36 deg for 10 command pulses to the motor. Figure 7 shows the travel accuracy with real-time compensation: The travel deviation decreases to less than 0.06 microns (RMS) over the total length of the stroke. The RMS value is approximately the value of σ_d in Figure 5.



(a) Travel error



(b) CAS

Figure 7: Travel accuracy with compensation

4. Conclusion

A new type linear actuator with nanometers level resolution was developed by integrating a coaxial differential ball screw with a stepping motor. It was confirmed experimentally that ultra-precise performance was realized using the actuator with travel deviation of less than 0.06 microns (RMS) and with fine positioning resolution of 5 nm. Thus, the superior performance of the developed actuator was verified, and the potential of the linear actuator using a CDBS was clearly demonstrated.

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