Development of an automatic cumulative-lead error measurement system for ballscrew nuts

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ORIGINAL ARTICLE

Development of an automatic cumulative-lead error measurement system for ballscrew nuts

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Abstract Ballscrew is a precision mechanical component used to convert rotational motion to linear motion in the precision linear stage. The precision measuring system for the screw's cumulative-lead error is already well known. Up to now, however, there is no suitable measuring equipment for internal cumulative-lead error of the nut. For a matching pair, it is not reasonable to understand the quality of only one piece. This paper presents a developed automatic cumulative-lead error measuring system for ballscrew nuts. The nut is clamped by a rotational stage, in which the moving angle is detected by a rotary encoder. The probing ball is inserted into the nut and remains in contact with the thread groove of the nut. The probe arm is mounted on a linear slide so that when rotating the nut, the probing ball will be pushed by the groove wall and moved axially. A high-resolution diffraction scale is employed to detect the linear movement of the probe to nanometer resolution. Combining the angular and linear motions, the cumulative-lead error of the nut can be realized. In practice, however, the nut will cause typical spindle errors during rotating, including axial slip, radial run out, and tilt motions. These errors have to be compensated in order to guarantee the accuracy of measurement results. A multi-sensor error compensation system is thus developed. Experimental results show the applicability of this developed measuring system.

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1 Introduction

The ballscrew is a high-efficiency feed screw with the ball making a rolling motion between the screw axis and the nut. It is commonly used in most machine tools to reduce the friction of the drive mechanism [1, 2]. Compared with a conventional sliding screw, this product has drive torque of one third or less, making it most suitable for saving drive motor power. The measuring system for the ballscrew's external lead error is normally designed similar to a long lathe. The ballscrew is mounted on a workpiece and fixed by an end center. A steel ball, same diameter as the inner ball of the ballscrew, is pushed in contact with the groove of the thread. The stylus of the steel ball is supported by an air-bearing stage that will move linearly along the guide way. A laser interferometer is employed to measure the linear displacement of the stage. When the ballscrew is rotated by the spindle, the steel ball will be pushed in the axial direction of the screw due to the helical angle of the groove, and thus, the linear stage will be moved accordingly. A simultaneous data sampling of the rotational angle of the screw by a rotary encoder and the corresponding linear motion of the contact probe by the laser interferometer can readily collect the cumulative-lead error of the ballscrew [3, 4]. It is, however, not easy to measure the same error of the ballscrew nut as it is to deal with the inner threads that, on one hand, are limited in space due to the small inner diameter of the nut and, on the other hand, the nut cannot be fixed by an end center. When rotating the nut, it exhibits unavoidable

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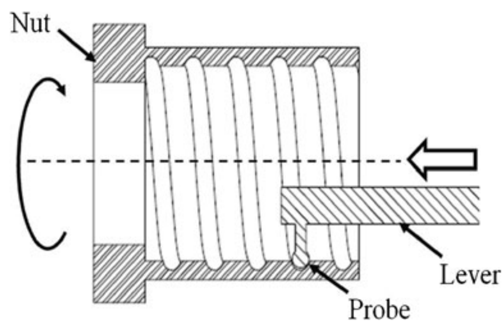


Fig. 1 Measurement principle of the ballscrew nut

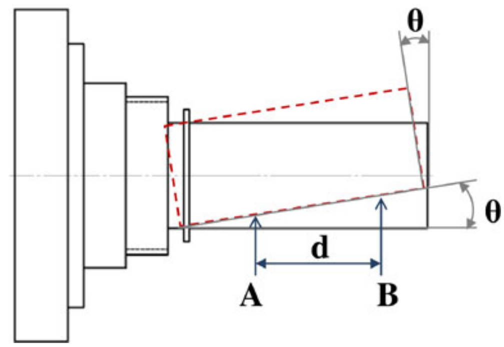


Fig. 3 Measurement of spindle tilt angle

rotational errors of run out and tilt, which will simultaneously generate systematic errors. There are only a few reports on the internal thread profile measurements of the nut, such as by a line laser with triangulation method [5], capacitive sensor [6], or fiber optic sensor [7, 8]. These reports did not compensate the above-mentioned systematic errors. Up to now, however, there is no suitable measuring machine for internal lead error of the nut.

This paper presents a developed automatic cumulative-lead error measuring system for ballscrew nuts. The measuring principle is similar to the cumulative-lead error measurement of the ballscrew. However, when clamping the nut at one end, conventional spindle errors will inevitably occur, namely the axial slip, radial run out, and tilt during rotation [9]. These errors have to be compensated in order to guarantee precise measurement results. A multi-sensor error compensation system is thus developed. Experimental results show the applicability of this developed measuring system.

2 Measurement principle

It is known that the ideal lead of the thread (L) is the multiplication of the rotational cycles and the pitch of the thread (P), as given in Eq. (1).

$$L = P(\phi/2\pi) \tag{1}$$

where φ is the rotational angle. In fact, the pitch may not be perfect. The actual lead should be measured by a displacement sensor. A simple schematic diagram is shown in Fig. 1. The probe head is inserted into the nut with the probing ball in contact with the side wall of the thread groove. Rotating the nut, the probe will be driven to linear motion by the thread due to the helical angle of the groove. The angle of rotation can be obtained by a rotary encoder, and the probe displacement is normally measured by a laser interferometer.

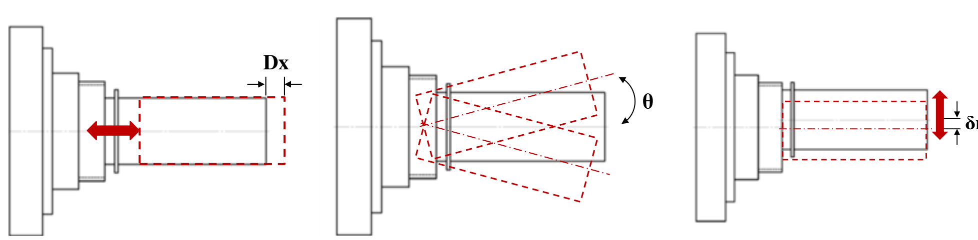
3 Compensation of spindle errors

Figure 1 is an ideal case that assumes no rotating errors of the spindle. In practice, in spindle rotation, there are three types of error that commonly influence the accuracy, namely the axial slip, the spindle tilt, and the radial run out, as shown in Fig. 2 [9]. Each of these will also induce the lead error measurement in the axial direction. Mathematical models corresponding to respective error types shall be derived for the purpose of error compensation.

3.1 Compensation of spindle tilt and axial slip errors

The spindle tilt can be measured by two displacement sensors at different axial positions, as shown in Fig. 3. The tilted angle θ can be expressed by Eq. (2). S_A and S_B are the measured gaps at point A and point B, respectively; d is the separation of two sensors.

Fig. 2 Three types of spindle rotation errors. **a** Axial slip. **b** Spindle tilt. **c** Spindle run out



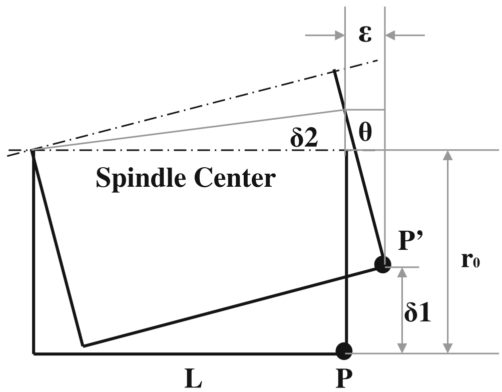


Fig. 4 Spindle tilt-generated axial slip

$$\tan\theta = (S_A - S_B)/d \tag{2}$$

Assuming a simultaneous movement of the probe with respect to the nut, the geometrical relationship of the axial slip (ε) of the probing point will be moving from P to P' when the nut is tilted by an angle θ, as shown in Fig. 4. The probe ball is in contact with the nut groove at the radial position r_0, and the length of measured nut is L. The axial shift of the probe ball caused by this tilt can be formulated by

$$\varepsilon = (r_0 - \delta_1 + \delta_2)\tan\theta = r_0 \tan\theta - \delta_1 \tan\theta + \delta_2 \tan\theta \tag{3}$$

Considering that the actual tilted angle is very small, Eq. (3) can be simplified by

$$\varepsilon \approx r_0 \tan\theta \approx r_0 \times (S_A - S_B)/d \tag{4}$$

The axial slip (D_x) of Fig. 2a can be measured by a separate gap sensor in the axial direction. Therefore, the total axial shift of the probing ball can be obtained as

$$\Delta X = D_X + \varepsilon = D_X + r_0 \times (S_A - S_B)/d \tag{5}$$

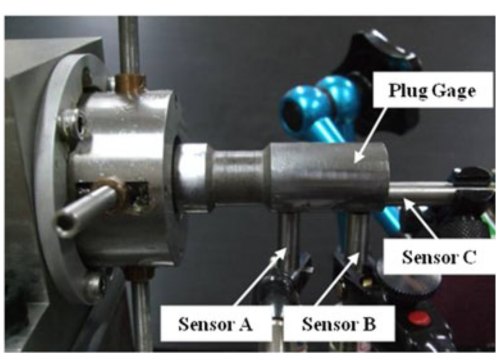


Fig. 5 Setup of tilt and axial slip measurement

Table 1 Specifications of tested ballscrew nut

Material	Alloyed steel
Screw groove	Gothic arch
Outer/inner diameter	50/30 mm
Outer/inner concentricity	0.37 μm
Lead	10 mm
Effective threaded length	50 mm
Ball diameter	3.969 mm
Matching ballscrew grade	C3 (JIS B1192:1997)

Figure 5 shows the experimental setup of spindle tilt and axial slip measurements. The tested ballscrew nut is provided by the biggest ballscrew manufacturer in Taiwan (Hiwin Co.). Its specifications are listed in Table 1.

A plug gauge is used as the tested spindle. Three noncontact capacitance sensors are used. These sensors are made by Tianjin University of China (model JDC-V; measurement range, ±400 μm; resolution, 0.1 μm; and linearity <1 %). Sensors A and B detect the tilted angle. Sensor C measures the total axial slip. Experimental results are shown in Fig. 6 for a full rotation of the nut. Compared with the theoretical calculation of the last term in Eq. (5) (r_0 is 5 mm and d is 20 mm), it is found that the theoretical error is less than ±0.6 μm, and D_X can be negligible. Therefore, data collected by sensors A and B can be used to compensate for the

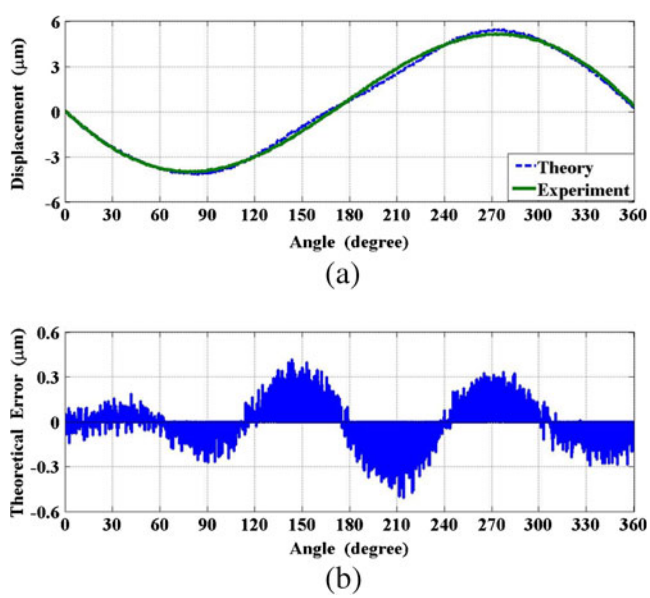


Fig. 6 Experimental results of axial slip measurement: **a** a full rotation, **b** theoretical error

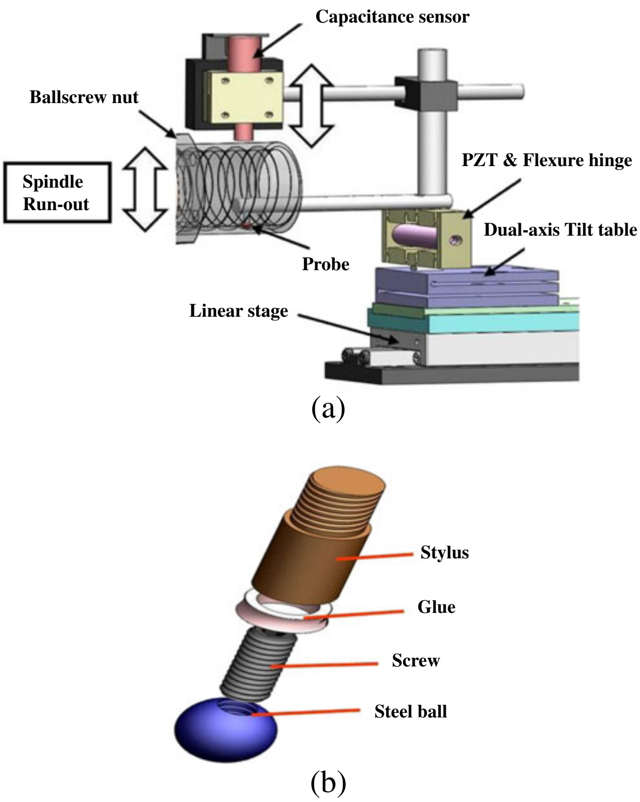


Fig. 7 Schematic of run-out compensation, **a** the measurement system and **b** the probe assembly

tilted angle-induced real-time probe moving error of Fig. 1.

It is noted that the effect of spindle run out of Fig. 2c has not been considered in Eq. (5). This part of the error is to be removed by a real-time adaptive compensation scheme as explained in the following.

3.2 Real-time compensation of spindle run out

The run-out motion of the nut will push the probing ball in up or down motion during measurement. A simultaneous movement of the probe with respect to the nut run out can be treated as no relative motion in between. This is the basic concept of the compensation system, as shown in Fig. 7a. The contact probe is specially designed, as shown in Fig. 7b, in which the end-ball is taken from the actual steel ball used in the same ballscrew. The contact force between the groove and the probe ball will drive the linear stage on which the perovskite-type lead zirconate titanate (PZT) mechanism and the capacitance sensor are mounted on. The sensor axis is in line with the probe ball so that it can detect the real-time run-out amount in the radial direction. The signal is processed with a low-pass filter and a microprocessor, from which a motion command to the PZT equipped flexure hinge mechanism can rapidly move the probe in vertical direction at a step same as the run-out displacement.

The flexure hinge is to amplify the PZT stroke. The principle of the flexure hinge mechanism is shown in Fig. 8a. When the input displacement of the link is ΔX in horizontal direction, the other end of the link outputs displacement ΔY in the vertical direction. Their relationships are:

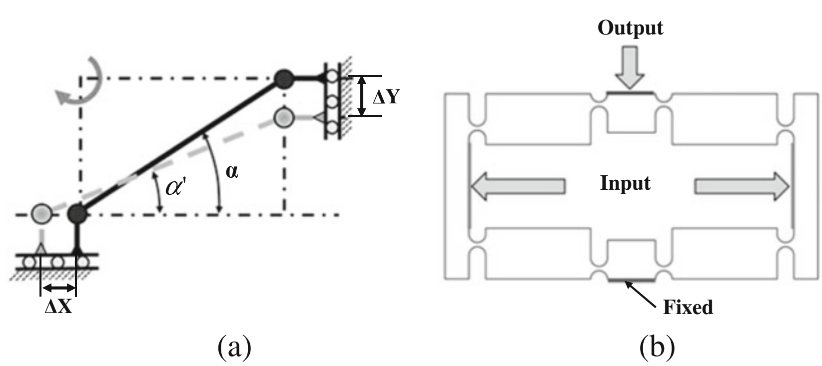
$$\begin{aligned} \Delta X &= L \times (\cos\alpha' - \cos\alpha) \\ \Delta Y &= L \times (\sin\alpha - \sin\alpha') \end{aligned} \tag{6}$$

where α is the initial link angle, α' is the link angle after displacement, and L is the link length, which is equivalent to one half of the width of the flexure mechanism, as shown in Fig. 8b. From Eq. (6), we have

$$\cos\alpha' = \frac{\Delta X}{L} + \cos\alpha \tag{7}$$

$$\sin\alpha' = \sqrt{1-\cos^2\alpha'} = \sqrt{1-\left(\frac{\Delta X}{L}+\cos\alpha\right)^2} \tag{8}$$

Fig. 8 Flexure hinge mechanism: **a** principle, **b** designed shape



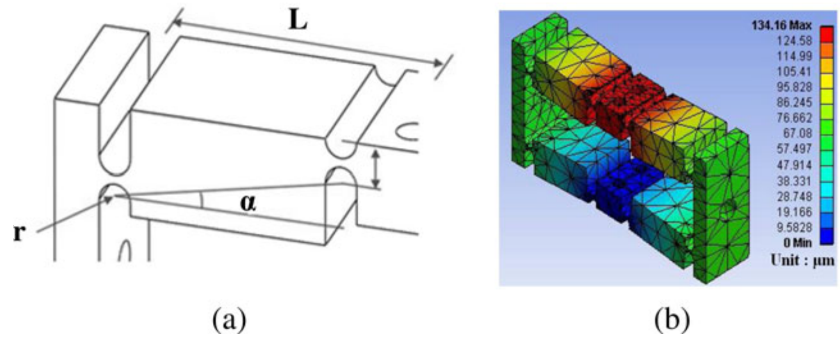


Fig. 9 Flexure hinge mechanism: **a** dimensional parameters, **b** FEA results

The amplification factor A can be obtained as

$$A = \frac{\Delta Y}{\Delta X} = \frac{L \sin \alpha - \sqrt{L^2 \sin^2 \alpha - \Delta X (2L \cos \alpha + \Delta X)}}{\Delta X} \quad (9)$$

The goal of this design is to increase the amplification as much as possible while the maximum stress remains within the yielding stress of the material. The finite element analysis (FEA) method is studied to obtain the proper dimensional parameters, as indicated in Fig. 9a. From trial and error tests under the constraint of maximum size and yield stress, parameters of L=20.3 mm, t=3.5 mm, r=1.4 mm, and α=11.5° were selected. The FEA result is given in Fig. 9b. With the use of aluminum alloy 7075 and at the PZT (model P-840.20 of PI Co.) stroke of 30 μm, the output is 134.16 μm. From the FEA method, the amplification factor is 4.472, and the safety factor is 12.5. Calculated by analytical method of Eq. (9), the amplification factor is 5.013, which is a little bit higher than the FEA method. Actual tests of the fabricated mechanism show that at 10-V input, the maximum output displacement is 129.27 μm, which is large enough for compensation. The design error is about 3.6 %, which is acceptable.

A proportional–integral–derivative (PID) control strategy is employed by a microprocessor (AVR of ATMEL Co.) having 10-bit ADC and DAC chips. The transfer function of PID is expressed by

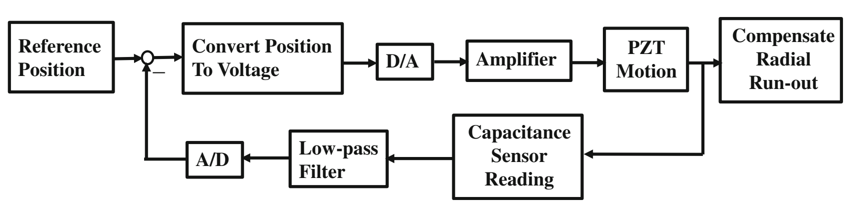
$$U(z) = \mathrm{KpE}(z) + \mathrm{Ki}\frac{\mathrm{Tz}}{z-1}\mathrm{E}(z) + \mathrm{Kd}\frac{(z-1)}{\mathrm{Tz}}\mathrm{E}(z) \quad (10)$$

where parameters of Kp, Ki, and Kd are to be tuned by the Ziegler–Nichols method for achieving the shortest settling time [10]. The dynamic response frequency of PZT is 0 to 2.7 kHz. The parameters were carefully tuned to achieve the settling time within 0.4 s. Figure 10 shows the block diagram of control loop for run-out compensation. In this block diagram, the reference position denotes the initial sensor reading position. Run out of the nut causes the sensor reading change. The microprocessor then generates a voltage to actuate PZT through an amplifier until the sensor reading returns to the initial position. In actual experiment, the nut was rotated at a low speed of 1 rpm. The outer diameter of the tested nut is 50 mm. The settling time of PZT causes the signal lag around 2° of the nut angle. Such a control strategy is possible to track the spindle run-out motion at a reasonable speed from the measurement point of view. Figure 11 shows the trajectory tracking of the developed PID control for four turning cycles. After compensation, the tracking error is less than ±0.5 μm throughout a full cycle of rotation. It demonstrates the proposed compensation strategy is satisfied.

4 Measurement system setup

The whole measuring system configuration is illustrated in Fig. 12. The nut to be measured is clamped by a four-jaw chuck, which is driven by a step motor at a low speed of 1 rpm. The initial centering and coaxial adjustments of the nut with respect to the chuck is assisted by a specially designed flexure hinge cylindrical plate. The instantaneous

Fig. 10 Control loop of run-out compensation



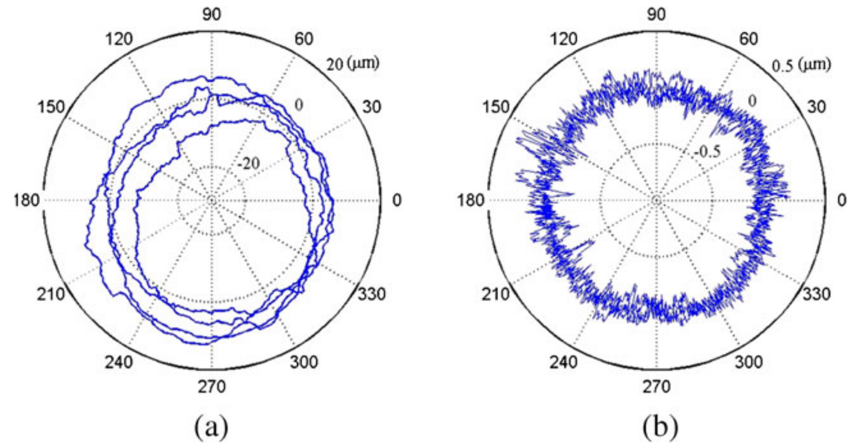


Fig. 11 Measurement of radial run out: **a** before compensation, **b** after compensation

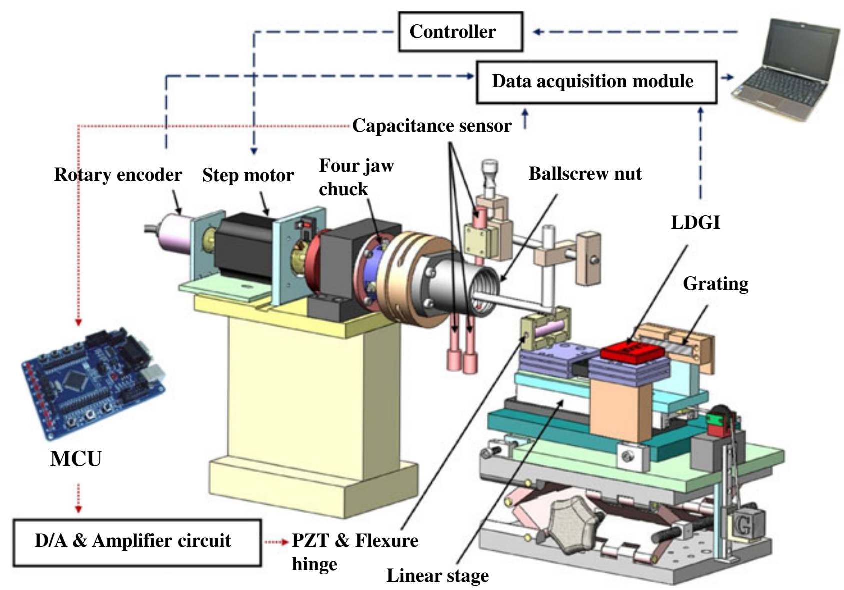


Fig. 12 System configuration of the measurement system

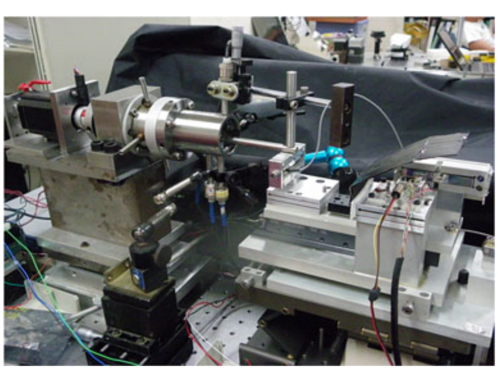


Fig. 13 Photo of experimental setup

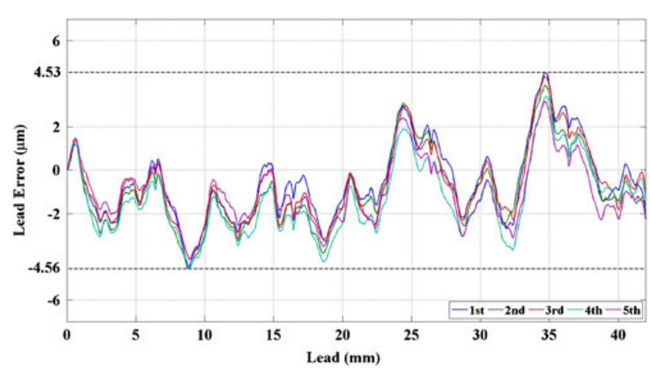


Fig. 14 Measured cumulative-lead errors of a ballscrew nut

angle is detected by a high-precision rotary encoder (laser encoder made by Canon Co.) to the resolution of 1 arc sec. The probe is extended to the inside of the nut through an extension arm that is fixed to the flexure hinge mechanism for initial alignment adjustment. The mechanism is mounted on a linear slide of cross-roller type. The probing ball is in sliding contact with the nut's internal groove surface. When rotating the nut, the probe will be pushed by the nut in the axial direction. The actual linear movement of the probe is detected by a holographic scale grating system, called linear diffraction grating interferometer (LDGI) previously developed by the author's group [11]. The resolution can reach 1 nm, and the accuracy is less than 30 nm for a long stroke up to 40 mm. Its performance is of the same grade as the laser interferometer, but its cost is much cheaper and its size is relatively much smaller. Figure 13 shows the photo of the developed measurement system.

5 Experimental results

The thread lead of the tested ballscrew nuts, provided by the manufacturer, is 10 mm, and the effective threaded length is 50 mm. Tests repeated five times were carried out for each sample. In each test, the LDGI reading is compared with the cumulative lead calculated by Eq. (1) in real time. The difference is defined as the cumulative error at each position. Figure 14 shows one of the results of a ballscrew nut. The measured cumulative-lead error is about 9 μm for the length of 42 mm. It corresponds to grade C3 as specified by JIS B1192:1997 standard. This is the same result as the company expected. It is noted that there is no obvious slope of the error curve because the nut is relative short in comparison with the ballscrew.

6 Conclusions

This paper presents a developed automatic cumulative-lead error measuring system for ballscrew nuts. The measurement principle is similar to that of ballscrew cumulative-lead error measurement. The nut is only one-end clamped, which results in inevitable spindle errors. A multi-sensor error compensation control system is thus developed for eliminating the induced probe motion error caused by these spindle errors almost in real time (0.4-s delay). A high accuracy diffraction interferometric scale is adopted to detect the linear movement of the probe to nanometer resolution. Combining the angular motion of the nut and the linear motion of the probe, the cumulative-lead errors can be realized.

The experimental results show that the developed measurement system can successfully measure the cumulative-lead errors of ballscrew nuts.

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