Precision Engineering 47 (2017) 452–458

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

# Design of high-precision ball screw based on small-ball concept

Tetsuya Miura [a,*], Atsushi Matsubara [b], Daisuke Kono [b], Kazuma Otaka [b], Kaoru Hoshide [c]

[a] Engineering Division, THK Co., LTD., 754 Nakadate Chuo-shi Yamanashi, 409-3801 Japan
[b] Department of Micro Engineering, Kyoto University, Katsura Nishikyo-ku, Kyoto, 615-8540 Japan
[c] Engineering Division, THK Co., LTD., 4-9-16 Higashikoujiya Ota-ku, Tokyo, 144-0033 Japan

ARTICLE INFO

*Article history:*
Received 14 June 2016
Received in revised form 8 August 2016
Accepted 6 September 2016
Available online 1 October 2016

*Keywords:*
Ball screw
Drive
Servo system
Position deviation
Torque fluctuation

ABSTRACT

This paper addresses a design method of ball screws for high-precision feed drives of machine tools. The torque fluctuation of a ball screw influences position deviation, which deteriorates the contorting accuracy. The torque fluctuation comes from the load change of the contacting balls between the nut and the screw shaft during ball circulation. In order to decrease the load change, a ball screw that employs smaller balls was designed and evaluated in the measurement tests. The experimental results showed that the designed ball screw could decrease both the torque fluctuation and position deviation.


## 1. Introduction

Feed drives are key elements that dominate the motion speed, stiffness, and accuracy of machine tools. The moving object (table, column, saddle) is driven by a linear motor, or a rotary servomotor via a ball screw [1]. The linear motor can drive the table directly at high speed (e.g., 240 m/min) and reduce positioning time under the high gain servo system [2]. However, in the case, where a large driving force is required, the required motor size becomes larger, thus increasing the difficulty in machine design and increasing machine cost. Therefore, linear motor drives are used in relatively small high-precision machines [3] and ultra-precision machines [4–6]. In contrast, ball screw drives are widely used for many types of machine tools. Using the ball screw, the combinations of force and feed speed could be flexible based on the lead of the screw. Additionally, the ball screw is compact, and the total cost of the drive system is not high.

In spite of the above-mentioned advantages, the application of the ball screw to high-precision machine tools is difficult. One of the problems is that the ball screw itself has flexible elements, balls and a screw shaft. To avoid axial vibration due to the flexibility, Erkorkmaz proposed vibration cancelation techniques such as notch-filter, adaptive sliding mode control [7], and active damping control [8]. Pritschow and Croon proposed re-design of the support-bearing unit to have lower stiffness and higher damping [9]. To increase the robustness, Gordon applied the pole placement and loop shaping to enhance the disturbance rejection function [10].

It is widely known that rolling elements in the ball screw and linear motion guideway have nonlinear relationships between the tangential friction force and the displacement. As the characteristic causes quadrant errors in circular motion, many compensation models have been studied [11]. Fukada et al. measured nonlinear elastic behavior of the ball screw using an original experimental apparatus and interpreted the measurement results into a viscous-elastic-plastic model [12]. To increase the stiffness of a ball screw, Verl proposed an adjustment mechanism consisting of nut preload [13]. Feng proposed a measurement method using an acceleration sensor to investigate preload variation of a ball screw [14].Guevarra et al. used a lapping process for the groove surfaces of screw shafts in order to improve travel variation and drunkenness [15]. There are much research regarding friction compensation, preload, and stiffness design of ball screws, however there is no significant research on avoiding the friction fluctuations that occur due to translation mechanisms and influence the servo errors.

In this research, the torque fluctuations of a ball screw and position deviations were measured using a torque measurement device and a test drive with an aerostatic guideway, and the position deviations were analyzed using the method proposed by Kono et al. [16]. Based on the analysis of the relation between the torque fluctuations and the position deviations, the load variation in the ball screw due to the ball circulation was targeted to be decreased. Ball

* Corresponding author.
*E-mail address:* te.miura@thk.co.jp (T. Miura).

http://dx.doi.org/10.1016/j.precisioneng.2016.09.020
0141-6359/

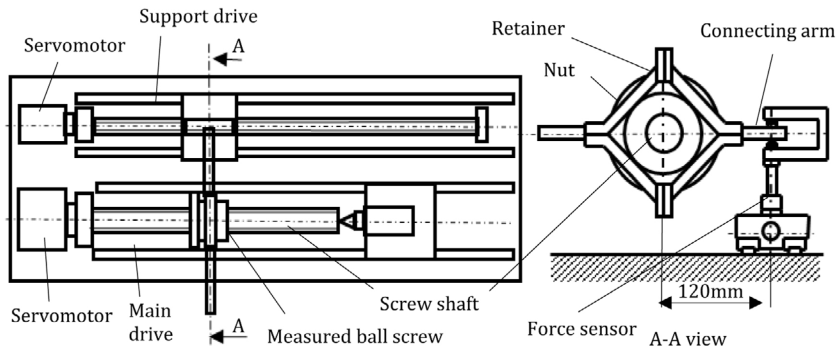


**Fig. 1.** Torque measurement devise.

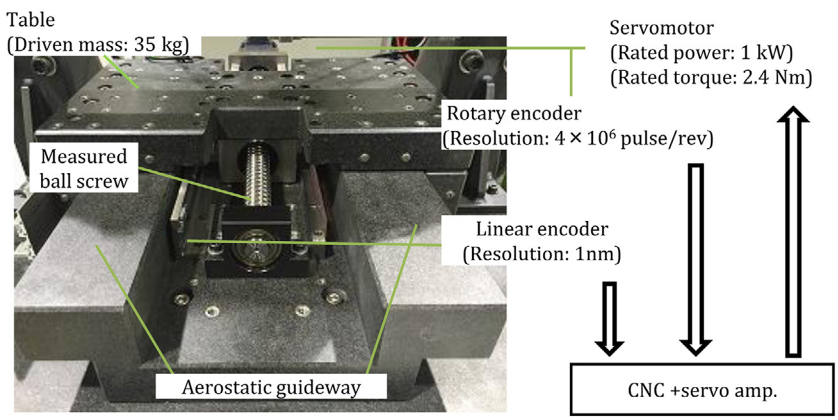


**Fig. 2.** Test drive for measurement of position deviation.

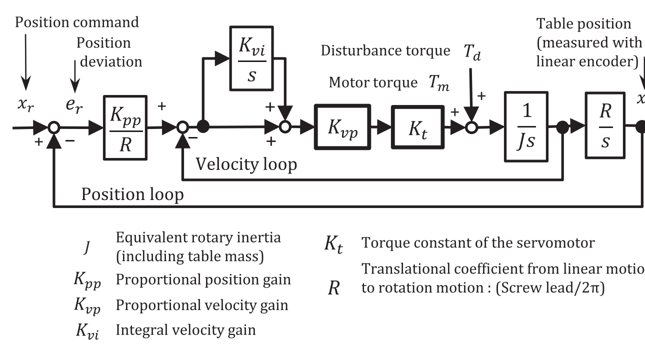


**Fig. 3.** Block diagram of the servo system.

screws were designed using smaller balls (small-ball concept) and evaluated in the measurement tests.

## 2. Experimental analysis

### *2.1. Measurement method*

Fig. 1 shows a measurement device for the analysis of a friction torque of a ball screw. A ball screw to be measured is rotated with a servomotor in a main drive. The rotation of the nut is constrained by a retainer, which is connected to the supporting drive with an arm. The main drive and the supporting drive move synchronously, which allows the nut to move on the screw shaft. A force sensor is installed at the end of the connecting arm, which measures the force required for the nut to resist rotation. The friction torque is estimated by multiplying the measured force and the distance between the centers of the two drives (120 mm). The friction torques were measured in backward and forward motions and repeated three times. Preload torque was adjusted at 0.12 Nm based on the ISO3408-3 [17]. Torque fluctuation was evaluated at a rotation speed of 15 min$^{-1}$.

Fig. 2 shows a test drive used to measure the position deviation in control motion. The ball screw, rotated by a servomotor, drove the table supported by a friction-less aerostatic guideway. The ball screw was mounted on the test drive, while keeping the runout of the shaft end within 3 μm and the parallelism between the screw shaft and the guideway within 10 μm.

For feed control, a market CNC controller with a drive amplifier was used. The control system employs a cascade of current-velocity-position loops. The block diagram is shown in Fig. 3. The motor position was detected by a rotary encoder for velocity loop, and the table position was detected by a linear encoder for position loop. The position deviation (shown as $e_r$ in Fig. 3) was logged using the measurement function of the CNC. Servo gains were set so that the velocity open loop had a gain margin of 10 dB and a phase margin of 40°. The bandwidth of the velocity feedback loop $\omega_{vc}$ [rad/s] is as follows:

$$\omega_{vc} = \frac{K_{vp} \cdot K_t}{J} \tag{1}$$

There exist notch filters in the velocity loop, which mainly suppress the torsional vibration resonance. The feed speed was selected from 120 mm/min to 3000 mm/min. Sampling period was set to 0.18 ms. The travel distance was set at 120 mm and the travel round-trips was 2 times. Analysis area of the position deviation was 80 mm to remove the areas of both ends 20 mm in order to steady-state velocity conditions.