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Study on a Novel Thermal Error Compensation System for High-Precision Ball Screw Feed Drive (2nd Report: Experimental Verification)

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KEYWORDS: Ball screw, Thermal error, Feed drive, Compensation

Real-time thermal error compensation of machine tool feed drive in general can be separated into three steps such as modeling, measurement and compensation. In the previous report, as the parts of the thermal error compensation system, component heat generation, compensation method, thermal model, mathematic model and calculation method were studied respectively. And a series of simulations was carried out in several kinds of working condition. And then, in order to discuss the correctness of the developed ball screw thermal error compensation system, a series of tests contains axial deformation, positioning accuracy, temperature variation and temperature distribution was carried out in the same working condition of prediction. As the results, the test data well confirmed the correctness of the developed ball screw thermal error compensation system.

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1. Introduction

In a machine tool, the three major types of errors are geometric errors, cutting-force included errors and thermal errors. Thereinto, the geometric errors make up the major part of the inaccuracy of a machine tool, the error caused by cutting forces depending on the types of tool and work piece and the cutting conditions adoped.[1,2] In a machine tool, continuous usage causes heat generation at the moving elements and this heat causes expansion of the various structural elements of the machine tool.[3-5] Expansion of the structural linkages of the machine tools that leads to inaccuracy in the parts positioning. Such errors are called thermal errors and constitute a significant portion of the total error in a machine tools.[6-10]

Real-time thermal error compensation of machine tool feed drive in general can be separated into three steps such as modeling, measurement and compensation. In order to achieve the final objective of eliminate the thermal error of the feed drive, the machine structure is first of all modeled through the use of finite element method or empirical method generally. Measurement of the temperature or positioning variation at critical elements on the machine tool feed drive is carried out using a variety of sensors. Once the temperature or positioning data are obtained, a compensation dosage is then arrived at that through the thermal behavior modeling. The traditional thermal error compensation system of ball screw feed drive is highly dependent on the feedback temperature or positioning data. The temperature and position measuring accuracy affect the thermal error compensate precision directly. Because of the overdependence to measuring technique, increasing of compensation system cost and decreasing of productivity level will be an inevitable trend in a machine tool.

In the previous report, as the parts of the thermal error compensation system, component heat generation, compensation method, thermal model, mathematic model and calculation method were studied respectively. And a series of simulations was carried out in several kinds of working condition. And then, in order to discuss the correctness of the developed ball screw thermal error compensation system, a series of tests contains axial deformation, positioning accuracy, temperature variation and temperature distribution were carried out in the same working condition of prediction. As the results, the test data well confirmed the correctness of the developed ball screw thermal error compensation system.

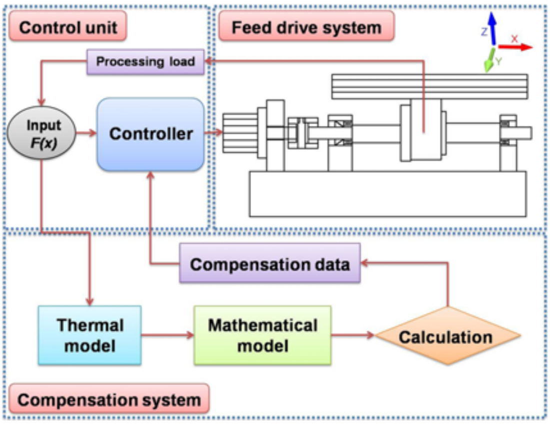


Fig. 1 Structure of ball screw feed drive thermal error compensation system

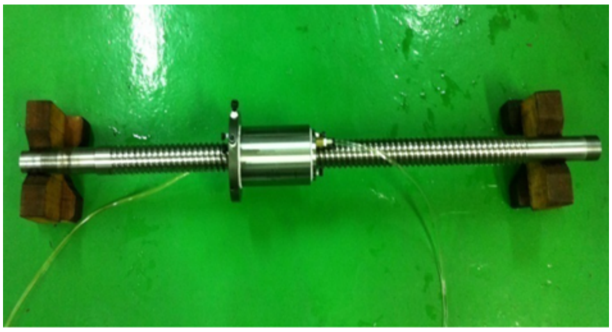


Fig. 2 Prototype ball screw used in thermal behavior simulation

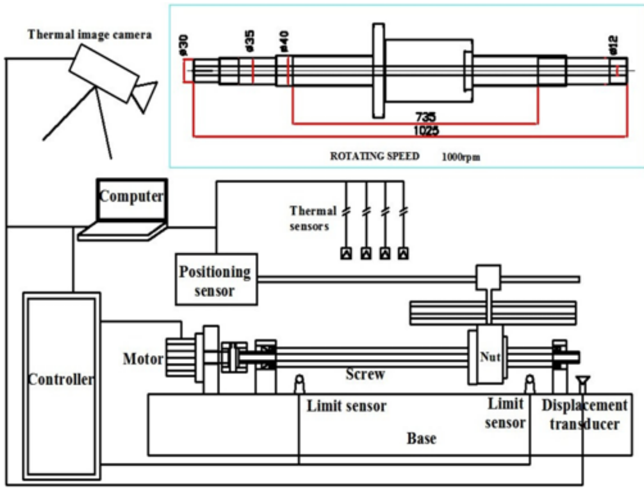


Fig. 3 Experimental set up

2. Structure of Compensation System

In the previous report, detailed description of the ball screw feed drive thermal error compensation system was done. The developed compensation system which can work without any feedback is shown in Fig. 1. This compensation system is a closed circuit system that no need for temperature or positioning feedback. The only input of this compensation system is the ball screw stroke input which can be obtained before the feed drive starting work. The compensation data will be obtained by calculating the input through the thermal model and the mathematical model. The controller of control unit can modify the stroke input by calculated compensation data to guarantee precise positioning of feed drive system as shown in this figure.

3. Experimental

3.1 Experimental set up

In order to evaluate the thermal model and the thermal error compensation system, a ball screw which shown in Fig. 2 was selected as prototype ball screw used in thermal behavior simulation. Two lines, an end-cap type, four point contact ball screw and ball bearings with 62 mm OD and 30 mm ID were used as specimens in this paper as shown in this figure. The main component parameters of the ball screw drive system which consists of ball screw shaft, ball screw nut and bearings. According to the parameters, heat productivity and convection coefficient can be calculated as the reason of thermal error prediction.

In order to discuss the correctness and generality of the developed ball screw thermal error compensation system, a series of tests contains axial deformation, positioning accuracy, temperature variation and temperature distribution was carried out in several kind of working conditions. A schematic diagram of experimental set up is shown in Fig. 3 which containing a ball screw,driving unit, data gathering unit (sensors) and control unit. The operator was able to control the motor to execute ball screw advance and return movement, and a computer was used to collect data from thermal sensors, positioning sensor, displacement sensor and thermal image camera. And the limit sensor can provide protection that can keep the nut away from the bearing brackets. The ball screw has 1025 mm total length; 735 mm groove processed length and 1000 rpm test rotating speed as shown in this figure.

3.2 Experimental method

In a machine tool ball screw feed drive system, moving stroke mode can broadly into three kinds of stroke: big stroke, small stroke and multy stroke cases. In order to verify correctness and generality of the thermal model and the thermal error compensation system, a series of simulations was carried out in several kinds of working condition which involves the above stroke cases. Fig. 4 shows the work conditions of a ball screw feed drive system which was same as the simulation conditions. Big stroke case is a simple reciprocating motion with 0.5 s pause, small stroke consists four 50 mm stroke (225~275 mm) and one 500 mm stroke (0~500 mm) and multy stroke consists three 50 mm stroke (225~275 mm) and two 500 mm stroke (0~500 mm) as shown in Fig. 9. Positioning data output points #1~#10 locate on 0 mm, 225 mm, 275 mm and 500 mm position of 500 mm full stroke as shown in this figure.

3.3 Results comparison

3.3.1 Total length

Through a series of experiments with the above set up, we obtained

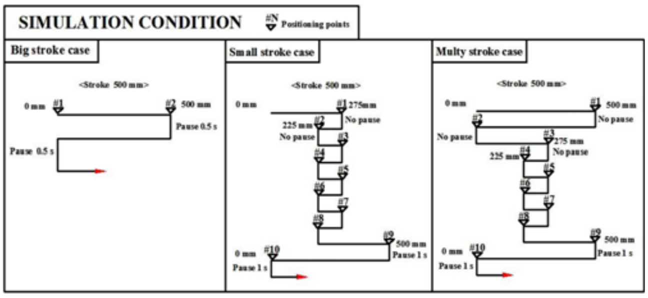


Fig. 4 Working conditions of a ball screw feed drive system

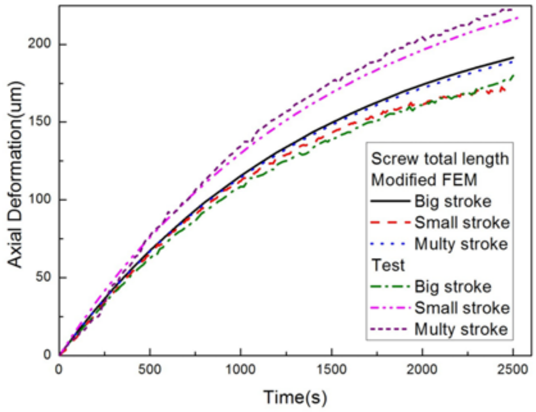
axial deformation, positioning accuracy, temperature variation and temperature distribution results under the simulation conditions as shown in Fig. 5. A comparison of the results of screw total length axial thermal deformation with measurement error less than 5% in rough is shown in Fig. 18 where figure (a) to figure (d) shows comprehensive comparison, big stroke case, small stroke case and multy stroke case respectively. It can be seen clearly from these figures that the screw total length axial thermal deformations from predicted results and tested results are very close.

3.3.2 Positioning

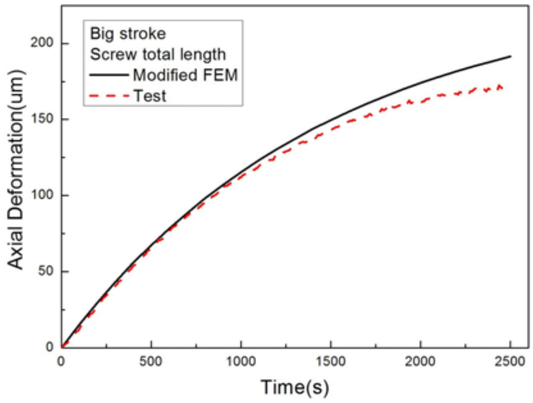
Figs. 6 to 8 show comparison results of predicted and tested positioning error variation in big, small and multy stroke cases. Fig. 6 shows comparison result of the predicted positioning error from data output points #1 and #2 and tested positioning error from 0 mm and 500 mm points of nut moving range in big stroke case. Figs. 7 and 8 shows comparison results of the predicted positioning error from data output points #1~10 and tested positioning error from 0 mm, 225 mm, 275 mm and 500 mm points of nut moving range in small stroke and multy stroke cases. It can be seen clearly from these figures that the positioning error variation tendency is similar in all the stroke cases. Even they have very similar variation tendency, but they also have a maximum error of about 13% (big stroke 13.07%, small stroke 13.28% and multy stroke 13.46%). The same pattern of these errors is that measured positioning data is smaller than predicted ones at the left side of nut moving stroke and measured positioning data is bigger than predicted ones at the right side of nut moving stroke. The reason for this error phenomenon is inertia of the moving ball screw nut and load. A sudden stop of the nut impact the screw and it causes axial deformation of screw and nut groove which generates the positioning deviation.

3.3.3 Temperature distribution

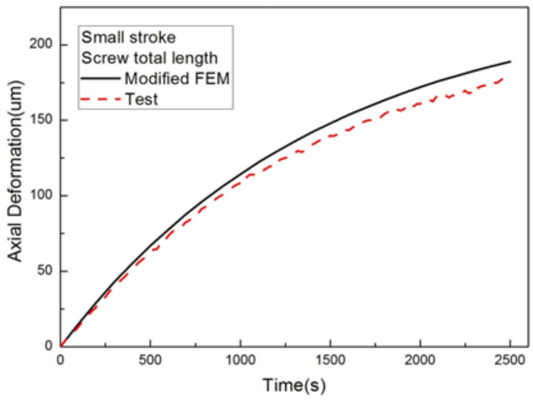
Fig. 9(a) shows comparison results of predicted and tested temperature distribution and variation in big stroke case on every 500 seconds. And Fig. 9(b) shows thermal images of ball screw surface in big stroke case which recorded every 500 s by a thermal image camera. Fig. 10(a) and 11(a) show comparison results of predicted and tested temperature distribution and variation in small stroke and multy stroke cases on every 500 seconds. And Fig. 10(b) and 11(b) show thermal images of ball screw surface in small stroke and multy stroke cases which recorded every 500 s by the thermal image camera. It can be seen clearly from these figures that tested data of temperature distribution



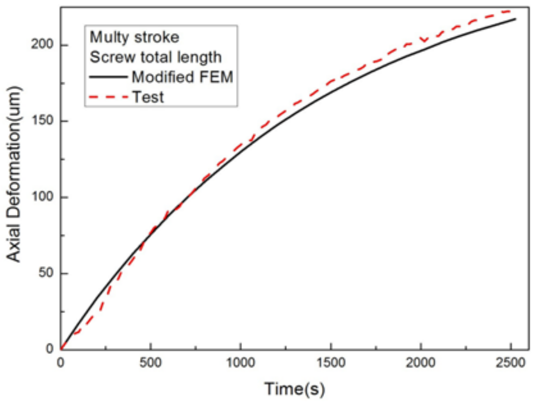
(a) comprehensive comparison



(b) big stroke case



(c) small stroke case



(d) multy stroke case

Fig. 5 Axial thermal deformation comparison (a) comprehensive comparison, (b) big stroke case, (c) small stroke case, (d) multy stroke case

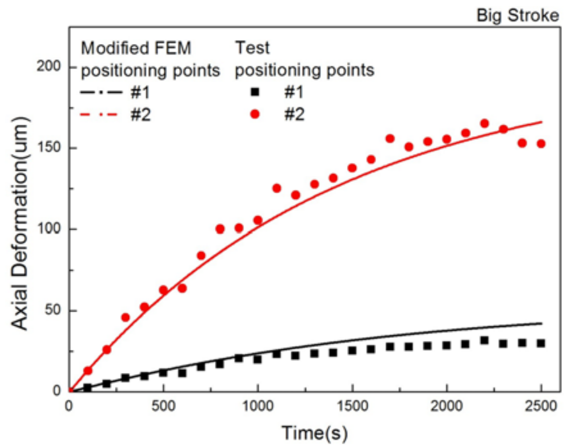


Fig. 6 Positioning error comparison in big stroke case

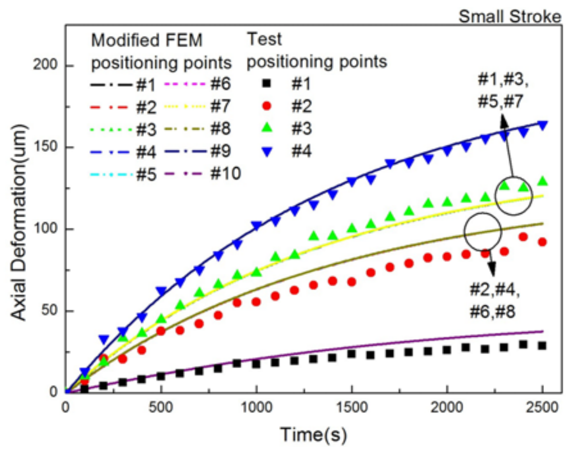


Fig. 7 Positioning error comparison in small stroke case

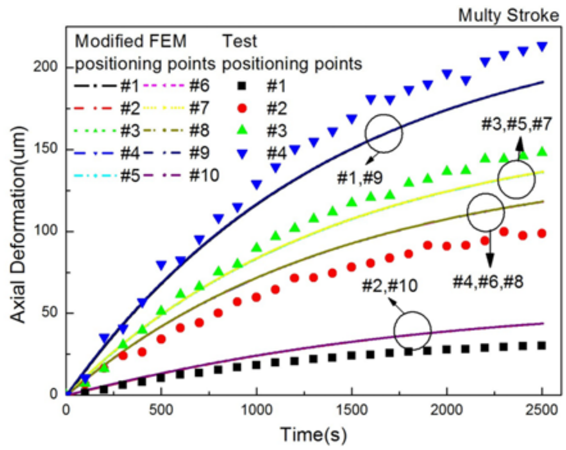


Fig. 8 Positioning error comparison in multy stroke case

and variation well confirmed the correctness of simulated results. And in the thermal image case, there is a grease sealing ring made by plastic on the nut part which results in the abnormal high temperature phenomena for the different emissivity of steel and plastic.

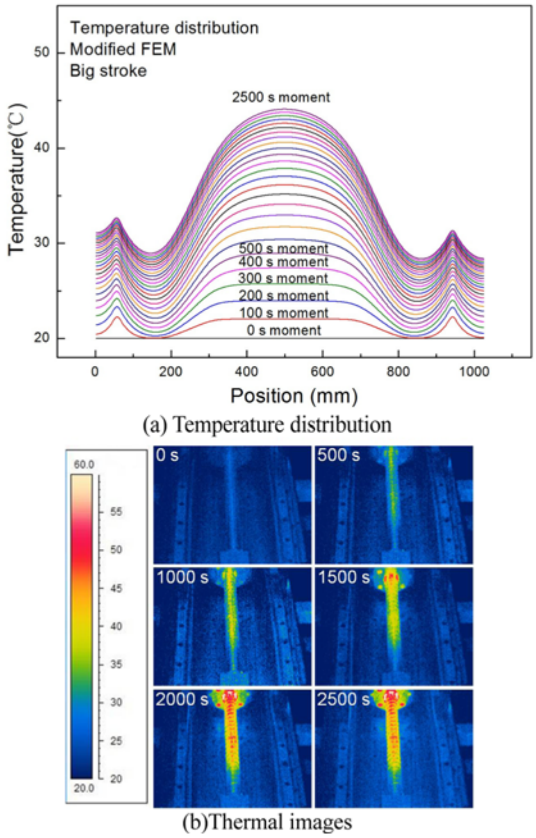


Fig. 9 Temperature distribution comparison in big stroke case

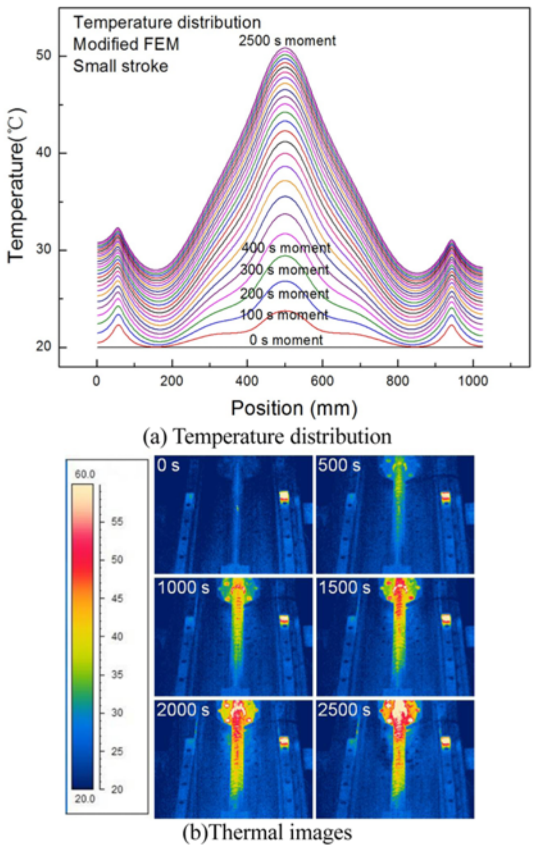
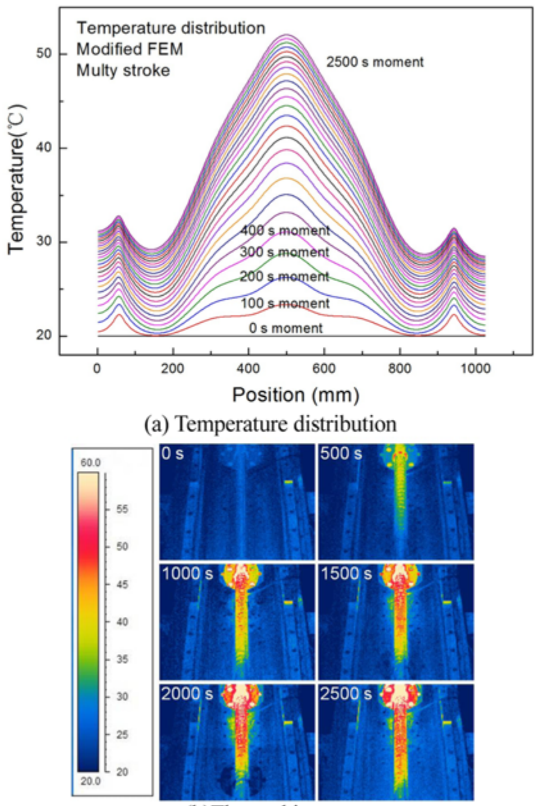


Fig. 10 Temperature distribution comparison in small stroke case



(a) Temperature distribution

(b)Thermal images

Fig. 11 Temperature distribution comparison in multy stroke case

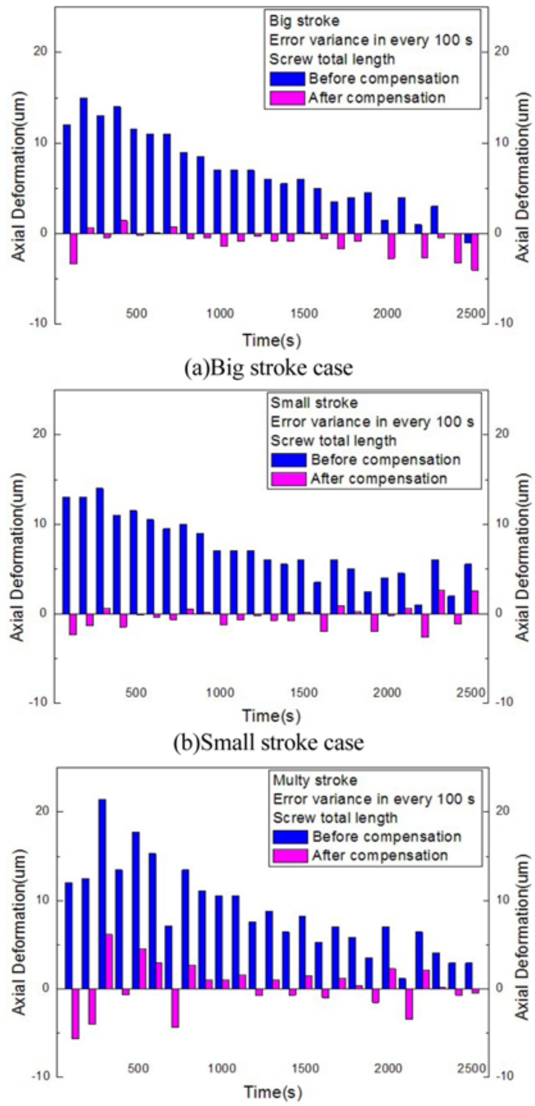
4. Results Analysis and Discussion

Fig. 12 shows comparison of 100 s error variance of screw total length axial deformation in big stroke, small stroke and multy stroke cases in 2500 s test time. The compensated 100 s error variance of screw total length deformation errors were controlled to less than 4 µm, 2.6 µm and 6.1 µm in big stroke, small stroke and multy stroke cases respectively.

Figs. 13 to 15 show comparison of 100 s variance of positioning error in big stroke, small stroke and multy stroke cases in 2500 s test time. Fig. 13 shows comparison result of 100 s positioning error variance before and after compensation from data output points #1 and #2 which located in 0 mm and 500 mm points of nut moving range in big stroke case. Figs. 14 and 15 show the 100 s positioning error variance before and after compensation from data output points #1 to #10 which located in 0 mm, 225 mm, 275 mm and 500 mm points of nut moving range in small stroke and multy stroke cases. A certain improvement of positioning performance by thermal error compensation was presented in these figures. Compare with the accumulative positioning error results, irregular variation tendency of compensated positioning error was presented in these figures. There are many possible reasons for this phenomenon such as measuring error, inertia of the moving ball screw nut and vibration of the feed drive.

5. Conclusion

In this paper, in order to discuss the correctness of the developed ball screw thermal error compensation system, a series of tests contains axial deformation, positioning accuracy, temperature variation and temperature distribution was carried out in the same working condition of prediction. As the results, the test data well confirmed the correctness of the developed ball screw thermal error compensation system. And in

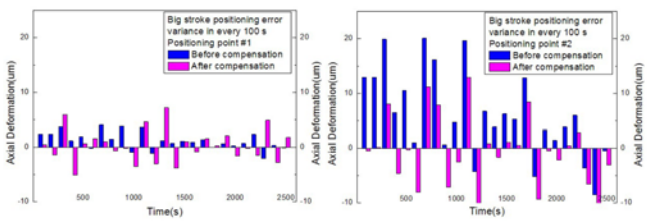


(a)Big stroke case

(b)Small stroke case

(c)Multy stroke case

Fig. 12 Comparison of screw total length axial deformation in every 100 s



(a)Positioning point #1 (b) Positioning point #2

Fig. 13 Comparison of every 100 s variance of positioning error in big stroke case

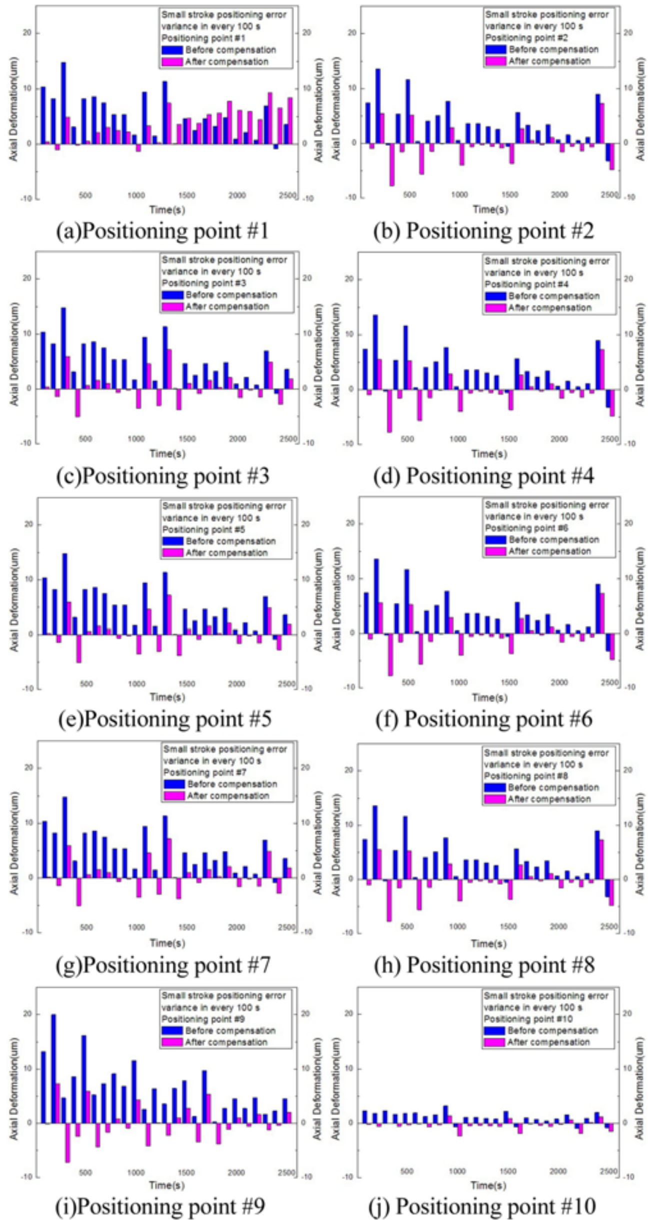


Fig. 14 Comparison of every 100 s variance of positioning error in small stroke case

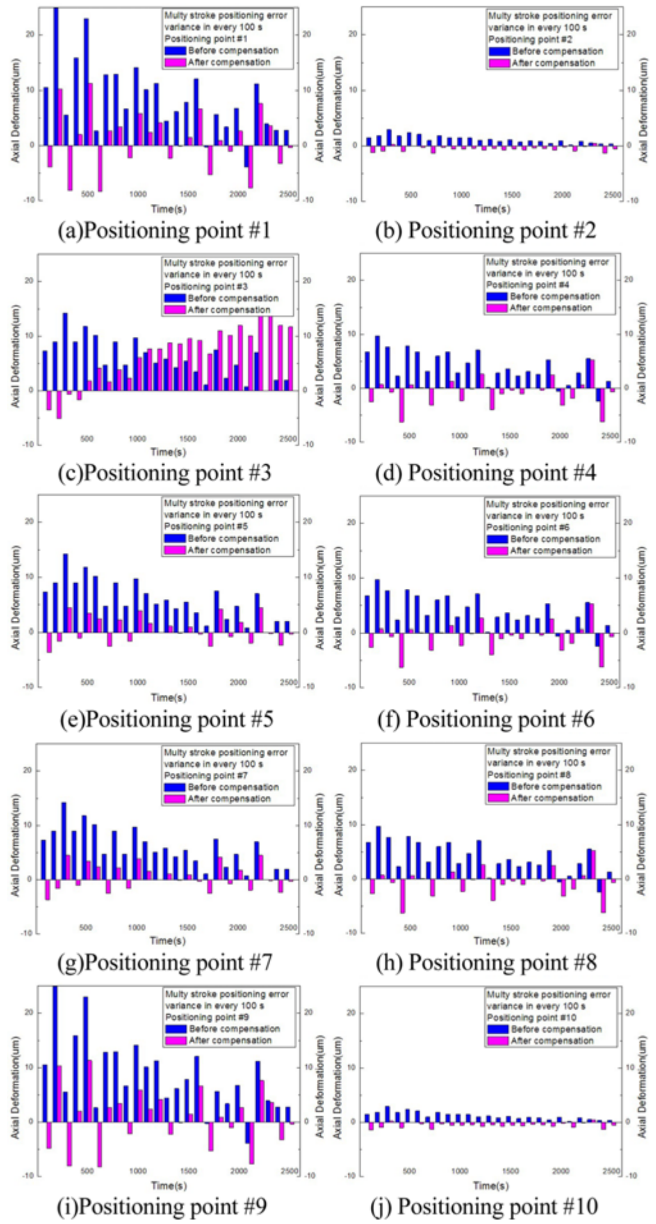


Fig. 15 Comparison of every 100 s variance of positioning error in multy stroke case

order to analyze the performance of thermal error compensation system, 100 s variance results of screw total length and positioning error were carried out. The compensated screw total length deformation errors were controlled to less than 22.5 μm, 12.9 μm and 13 μm and improved but irregularly varying positioning performance of 100 s variance by thermal error compensation was presented. There are many possible reasons for this phenomenon such as measuring error, inertia of the moving ball screw nut and vibration of the feed drive.

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