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Study on Thermal Error Elimination for a Ball Screw Feed Drive

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***Abstract*—The traditional thermal error compensation system of ball screw feed drive is highly dependent on the feedback temperature or positioning data. 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. This paper presents a new approach in ball screw thermal error compensation system which can work without any temperature or positioning feedback. As the parts of the thermal error compensation system, component heat generation, compensation method, thermal model, mathematic model and calculation method were studied respectively. In order to discuss the correctness of the developed thermal error compensation system, a series of tests contains positioning accuracy 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**

***Keywords*—Ball Screw, Thermal Error, Feed Drive, Error Compensation, Calculation Method, Positioning Error**

I. Introduction

In general, in order to compensate the thermal error or the positioning error of a ball screw feed drive system, the actual temperature or positioning data feedback was needed.[1-4] This paper presents a new approach in ball screw thermal error compensation system which can work without any temperature or positioning feedback. As the parts of the thermal error compensation system, component heat generation, compensation method, thermal model, mathematic model and calculation method were studied respectively. In order to verify correctness and generality of the developed thermal model and the thermal error compensation system, a series of simulations was carried out in several kinds of working condition. Through the series of simulations with the thermal model, calculation method and simulation conditions, deformation characteristics and thermal behavior of the prototype ball screw system have been obtained. In order to discuss the correctness of the developed thermal error compensation system, a series of tests contains positioning accuracy 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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II. Thermal model for compensation system

The demand for higher productivity and tight part tolerances requires machine tools to have faster and more accurate feed drive systems. A high-speed ball screw drive system generates more heat and results in greater positioning error. In a ball screw drive system, there are two main heat sources which contains support bearings and ball screw nut. Friction between the balls and races of the bearings is the predominant reason for temperature elevation in a ball bearing.

For the purpose of this paper, use of the finite element method (FEM) as an important thermal error analysis method must be based on the following assumptions.

1. Grooves on the screw shaft are negligible: in other words, the screw shaft is a hollow cylinder.
2. Frictional heat generation from the nut and bearings is a constant value.
3. The heat convection coefficient is a constant value, not related temperature, or the moving and stopping.
4. The effect of heat conduction through lubricant and thermal deterioration is negligible.

Even the general thermal models[5,6] of FEM and MLCM can well predict the thermal behavior of ball screw system, but they exists some fatal flaws such as lack of generality and overmuch prerequisites. In order to build exact ball screw thermal model, a detailed thermal analysis of ball screw feed drive system was needed. In ball screw drive system, there are some main heat sources which contains support bearings(q_1 and q_3), ball screw nut(q_2) and motor(q_0) as shown in Fig. 1. In this figure, q_4 presented heat dissipation by air convection and $q_5 - q_7$ presented conductive heat dissipation through bearing bracket and nut supporting structure. A modified finite element model for the ball screw drive system was developed as shown in Fig. 2. The thermal model contains two bearing constant themo-genesis loads, a moving nut constant themo-genesis load and convective heat transfer boundary on the linear elements. And the modified finite element thermal model was established with FORTRAN language.

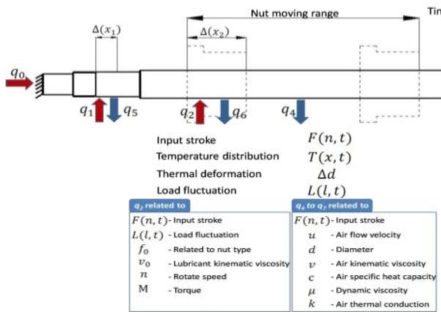

Fig. 1 Ball screw feed drive system thermal analysis

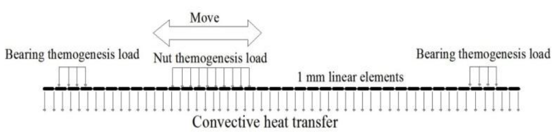

Fig. 2 Modified finite element model

III. Calculation method for compensation system

A. Calculating flow

Calculating flow of modified finite element thermal model which contains motion equation input, loop in move, loop in stop and results output was shown in Fig. 3. In the calculation process, the motion equation input to the meshed thermal model to obtain the input heat which causes loop in move and loop in stop. And through the two loops, the temperature distribution and the thermal deformation can be calculated as shown in this figure.

B. Calculation method

In view of the axial symmetry of ball screw, in order to reduce the amount of calculation, 3D model is substituted into 2 d model. Total length of Experiment device of screw is 1025 mm. According to the total length of screw, nut and screw pitch, total time of nut-moving can be figure out as 2530 seconds. First of all, according to the proportion, actual size of ball screw is assigned values to divided 1025 units.

Specific operation is Calculate the diameter, perimeter and volume of ball screw then assignment respectively. "Generate_mesh" function is created, used for return the assignment data of each unit finite element. Next to the nut movement trajectory calculation, divided into three kinds: big stroke case, small stroke case, multy stroke case. Because these three kinds of movement are different, that means nut

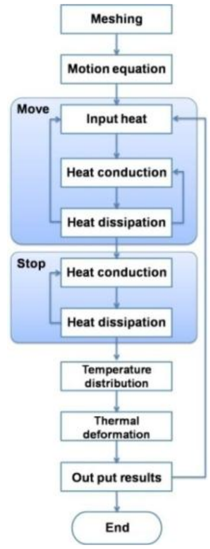

Fig. 3 Calculating flow of FE thermal model

move time, number of movements, pause time, pause frequency are not the same. So the three kinds of variable parameters are created, they are nut single move time, single pause time, moving rate (pitch). On this basis, define other public parameters, such as move range, specific heat capacity, air density, material density, the convection coefficient.

In order to calculate the temperature distribution, generated heat of finite element unit need to calculated step by step. In programming, input_heat, heat_trans, output_heat functions are created to calculate heat generation. And the main formulas of computational process of functions are shown in fig. 5.

IV. Constitute of compensation system

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 minimizing thermal error in the machine tool feed drive, the machine structure is first of all modeled through the use of finite element method or empirical method. 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.

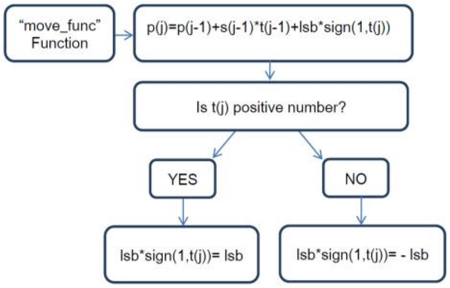

Fig. 4 Computational process of "move_func" Function

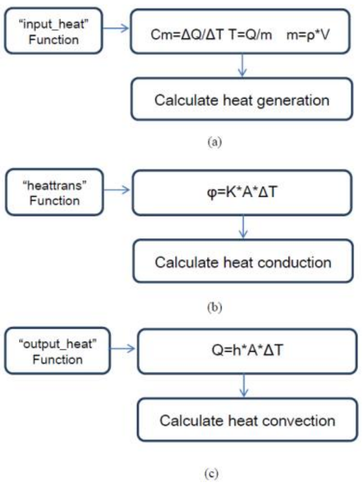

Fig. 5 Formula of computational process of Function

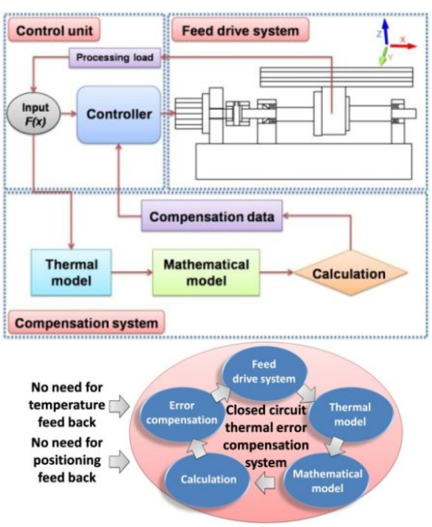

Fig. 6 Improved ball screw feed drive thermal error compensation system

Improved ball screw feed drive thermal error compensation system which can work without any feedback is shown in Fig. 6. 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.

V. Experimental verification

A. *Test piece and experimental method*

In order to evaluate the thermal model and the thermal error compensation system, a ball screw 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. In order to discuss the correctness and generality of the developed ball screw thermal error compensation system, a series of tests contains positioning accuracy and temperature distribution was carried out in several kind of working conditions. A schematic diagram of experimental set up is shown in Fig. 7 which containing a ball screw, driving unit, data gathering unit (sensors) and control unit. Fig. 8 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 mm ~ 275 mm) and one 500 mm stroke (0 mm ~ 500 mm) and multy stroke consists three 50 mm stroke (225 mm ~ 275 mm) and two 500 mm stroke (0 mm ~ 500 mm).

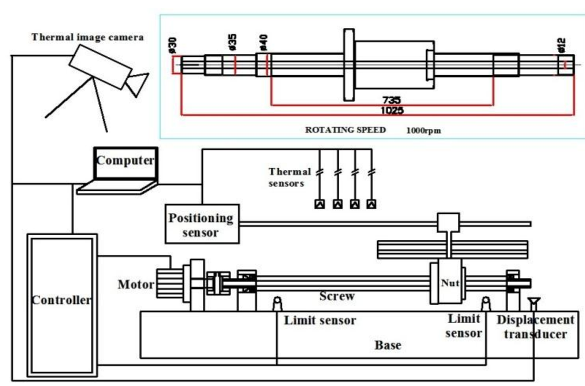

Fig. 7 Experimental set up

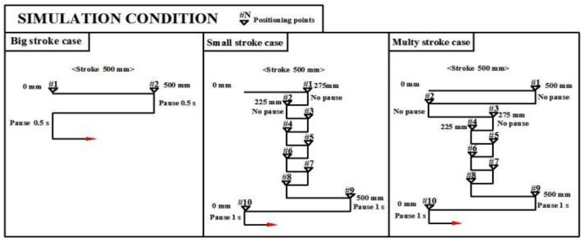

Fig. 8 Working conditions of a ball screw feed drive system

B. *Positioning*

Fig. 9 to Fig. 11 show comparison results of predicted and tested positioning error variation in big, small and multy stroke cases. Fig. 9 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. Fig. 10 and 11 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.

C. *Temperature distribution*

Fig. 12 shows comparison results of predicted and tested temperature distribution and variation in big stroke case on every 500 seconds. Fig. 13 and Fig. 14 show comparison results of predicted and tested temperature distribution and variation in small stroke and multy stroke cases on every 500 seconds. It can be seen clearly from these figures that tested data of temperature distribution 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.

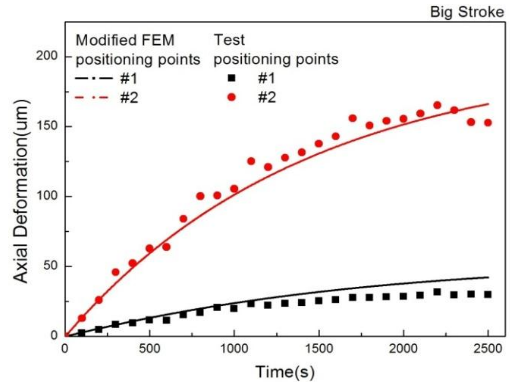

Fig. 9 Positioning error comparison in big stroke case

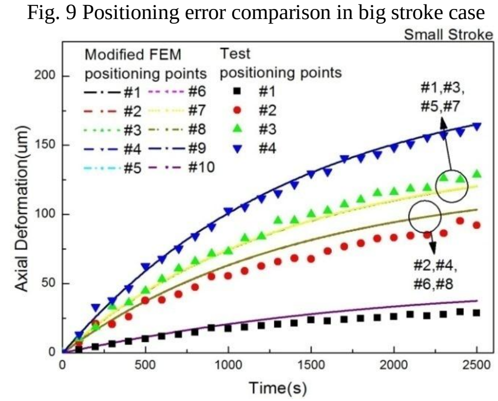

Fig. 10 Positioning error comparison in small stroke case

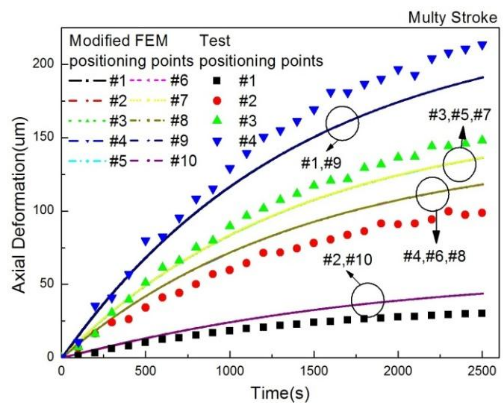

Fig. 11 Positioning error comparison in multy stroke case

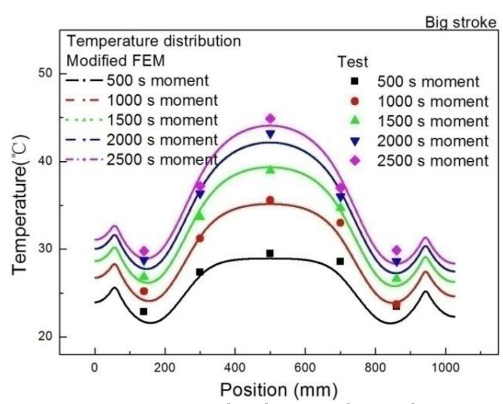

Fig. 12 Temperature distribution in big stroke case

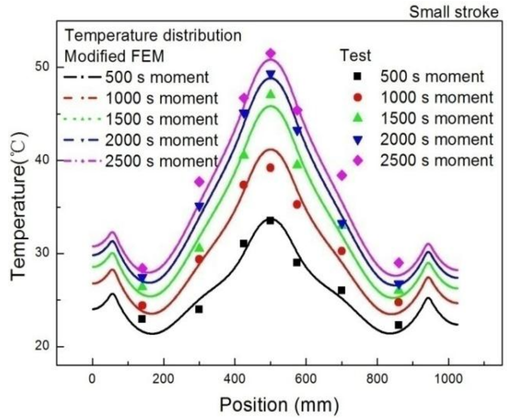

Fig. 13 Temperature distribution in small stroke case

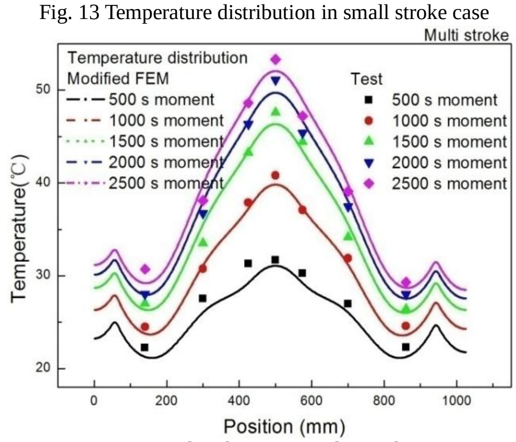

Fig. 14 Temperature distribution in multy stroke case

VI. Conclusion

The final objective of this thesis is that eliminate thermal errors of machine tool feed drive system efficiently and with low cost. In order to achieve the final objective, modified ball screw thermal error compensation system which can work without any feedback and a novel/well designed high speed/high precision nut/screw air cooling ball screw system were carried out respectively in this thesis.

This thesis presents a new approach in ball screw thermal error compensation system which can work without any feedback. For develop the thermal error compensation system, component heat generation, compensation method, thermal model, mathematic model and calculation method were studied respectively. In order to discuss the correctness and generality of the developed ball screw thermal error compensation system, a series of simulations and tests contains positioning accuracy and temperature distribution by the prototype ball screw system was carried out. As the results, the test data well confirmed the correctness of the developed ball screw thermal error compensation system.

As the results, 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. And in the temperature distribution case, the tested data of temperature distribution and variation well confirmed the correctness of simulated results.

Acknowledgment

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