SUPERVISING AND COMPENSATION OF THERMAL ERROR OF CNC FEED BALL SCREW

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Summary

The paper presents a set allowing for on-line monitoring of machine tool feed screw temperature. Indirect supervising of the feed screw thermal elongation protects ball bearings from excessive loads. Moreover, the usage of an appropriate model in the control system of the CNC machine tool allows for the reduction of ball screw thermal errors.

Keywords: thermal error, feed screw, monitoring

NADZOROWANIE TERMICZNE ORAZ KOMPENSACJA BŁĘDÓW ODKSZTAŁCEŃ CIEPLNYCH ŚRUB POCIĄGOWYCH OBRABIAREK CNC

Streszczenie

Prezentowany w pracy układ pozwala na monitorowanie „on-line" temperatury śruby pociągowej obrabiarki. Pośredni nadzór wydłużenia cieplnego śruby zabezpiecza przed nadmiernym obciążeniem łożysk tocznych na skutek wydłużenia cieplnego śruby pociągowej. Dodatkowo zastosowanie odpowiedniego modelu w systemie sterowania obrabiarki CNC pozwala na redukcję „on-line" błędów pozycjonowania wynikających z odkształceń cieplnych śrub pociągowych obrabiarki.

Słowa kluczowe: odkształcenia cieplne, śruba pociągowa, monitoring

1. INTRODUCTION

The heat generated as a result of friction in cooperating elements of manufacturing machines is a common adverse phenomenon. An increase in the temperature of machine sub-assemblies leads to a deterioration of machine accuracy. In extreme cases generated heat can lead to seizure or even destruction of machine parts. In industrial machines the temperature measurement transmitted via LAN networks allows for remote diagnostics [1, 2, 3]. In modern CNC machine tools it is common to monitor the working temperature of the spindle bearings and temperature of motors equipped with permanent magnets [4, 5].

In CNC machine tools thermal deformations increase the volumetric error, thereby they may cause the tolerances imposed on the machined workpieces no to be met [6,7].

The aforementioned examples show the importance of the temperature monitoring in modern manufacturing. In this paper the attention is given to thermal deformations accompanying the work of the ball screw driven feed axes of CNC machine tools.

In the CNC feed axes utilising ball screws there is a need of reducing the impact of thermal phenomena on the system's functioning. For example, the proper selection of the bearings clearance requires considering the radial thermal expansion of the shaft, which result from external heat sources. Another issue, which must be resolved by constructor, is the selection of an appropriate bearing arrangement. E.g. the "X" arrangement is characterised by the bearings load increase as a result of the shaft thermal elongation. Whereas, the bearing mounting in the "O" arrangement is characterised by a decrease in the load of bearings along with the thermal expansion of the shaft.

In the case of drive axes utilising ball screws, often apart from the pretensioning of the screw, the pretensioning of the nut-screw bearing is applied to increase the rigidity. In this case, it is important to consider the axial thermal expansion of the screw. It is, because the large mass of the machine body and existing heat flow will lead to significant difference in machine body and screw temperature. The considerable elongation of the screw relative to the body will take place if the screw is long enough, the friction moment is high due to the pretensioning of the nut, the thermal resistance between the screw and the body is high. In such case, an insufficient axial clearance in a non-locating bearing will lead to the destruction of the mechanism [9].

2. THE TEMPERATURE MONITORING AND POSSITION CONRECTION SYSTEM

2.1 System of Screw Temperature Monitoring

The presented system for the feed screw temperature monitoring, designed primarily for the purpose of reducing the impact of thermal errors of the feed screw on the accuracy of the CNC machine, additionally allows for an indirect measurement of the total feed screw elongation in order to secure the machine against dangerous thermal deformation levels.

It also enables the monitoring of the feed screw ball bearing temperature. Increased temperature of the bearing unit is an alarming signal and may prove inadequate working conditions or be a symptom of failure [10, 11]. Monitoring of this temperature provides valuable information about the system wear.

In the presented set for the thermal monitoring, the NTC temperature sensors were placed in the ball screws [12] of a numerically controlled milling machine AVIA VC 760. They have been mounted within the distances of 135 mm from each other by means of a thermoconductive glue which prevents the sensors from the negative influence of external factors. The first and the last sensor are located directly under the ball bearings. The lead out of wiring (Fig.1.) takes place via an axial bore placed in the centre of the screw. The axial bore, after placing signal wires in it, was filled with adhesive silicone. Cables are thus secured against a relative rotational movement in relation to the rotating screw, caused by the inertia of the cables. This movement could result in the twisting of the wires or cables being cut by sharp steel edges.

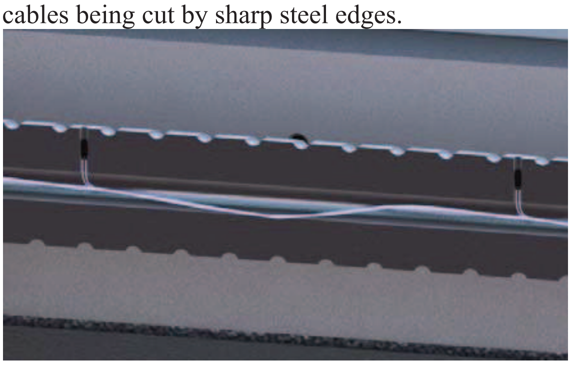

Fig. 1. Visualisation of the NTC sensors mounted in the feed screw

Leading out the signal from the screw takes place via the rotary electrical connector. In industrial application it is advisable to place a multi-path connection between the sensors and the rotary connector, allowing for fast replacement of the rotary connector worn as a result of operation or ensuring wireless data transmission.

Fig. 2. Photo of the AVIA VC760 machine tool bearing node along with a connector providing the possibility of the sensor system rotation

In the presented example, a single bearing unit of the screw consists of a pair of angular bearings in the back to back arrangement. Bearing units of the screw, along with the screw itself, were preloaded by means of tightening the bearing nuts with a tension wrench, providing the preload suggested by the manufacturer. Rolling bearing interface between the nut and the screw has been initially pretensioned by gear supplier.

2.2. Control System

The temperature measurement for the purposes of monitoring may be conducted and analysed regardless of the work of the CNC machine tool control system. However, the compensation of thermal deformations on-line requires a continuous data flow between the control system of CNC machine and the module calculating the position corrections. This is caused by the dependence of the position correction from the present position of the table and a temporary distribution of the screw temperature function.

In the constructed set, the resistance temperature signals are subject to acquisition by means of National Instruments measurement converters, and then sent through the ITP/UDP protocol to the PLC of the machine tool.

In the industrial application, the data acquisition module type would be dependent on the measurement modules offered by the vendor of the machine control system. It should be noted that usually the most convenient and reliable solution is the application of modules directly recommended by the control system manufacturers.

The algorithm of the control system including thermal deformation correction implemented in a manner unnoticeable to the machine tool operator can be created on the basis of the structure of virtual axes (Fig. 3).

The architecture of virtual axes has been implemented by B&R for precise synchronisation of multi-axis drives [5]. In this solution, the virtual axis, which is only a software unit, is a master unit for the slave physical units. Transmitting the set position via the Powerlink interface, at intervals of 400ms, to the slave units ensures synchronisation.

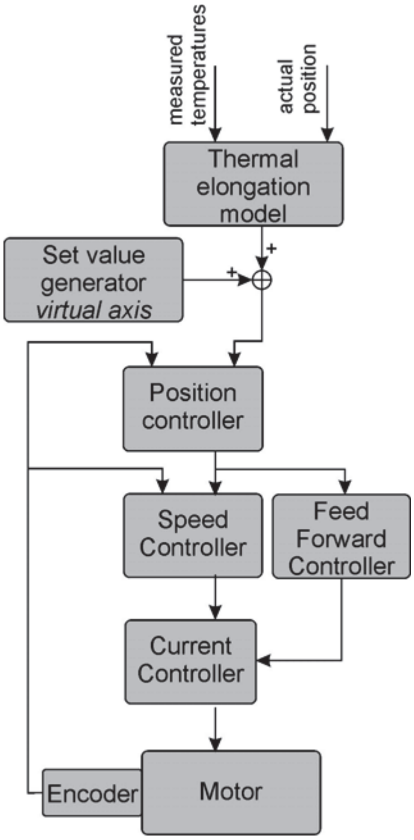

Fig. 3. The diagram of the control system of a single axis

The aforementioned structure has been implemented in the presented solution. B&R ARNCO libraries containing the full structures of the CNC drives, have been used for this purpose. The structure includes i.e. G-code interpreter, trajectory generator, drive regulator and complex geometric error compensation structures. A virtual, 3-axis CNC structure was created. It sends the set positions summed with the thermal deformation corrections to slave physical units operating in the follow-up system. In this way, it was possible to introduce on-line corrections of the drives positions.

2.3. Positioning Accuracy Measurement Set

The measurement of the positioning accuracy was performed with a Renishaw XL80 laser interferometer. First interferometer mirror was mounted on the machine tool table and the second one on the headstock. Additionally, sensors measuring the temperature of the moving table, the temperature of the body on which the table moves, and the temperature of headstock columns were installed. A picture of the measurement station is presented in Fig. 3.

Fig. 4. AVIA VC760 machine tool equipped with screws with temperature sensors during the measurement of positioning accuracy

3. MODEL OF DEFORMATIONS

3.1. Introducing the Model of Screw Deformations

It is assumed that the ball screw and the bearings can be modelled as a one-dimensional heated bar restrained on both sides by springs (Fig. 5).

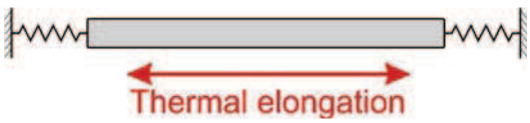

Fig. 5. Model of feed screw deformations

The screw temperature was approximated by a linear spline which adopts the values recorded by the temperature sensors in the nods. Integrating the screw temperature in the function of its length and multiplying the obtained value by the thermal expansion coefficient provides us with the information on the screw elongation.

It was assumed that the rigidity of both bearings unit is the same and that their rigidity is constant as they deform.

In order to calculate the displacement of a point located on the screw, it was necessary to transform the CNC control system coordinates to the coordinate system connected directly with the physical location of the nut on the bolt.

3.2. Tuning the Model

In order to tune the analytical model, a series of the measurements lasting about 3 hours were conducted. Initially, the positioning accuracy of the machine being in a state of thermal equilibrium with the environment was measured. Then, a cyclic movement of the table was turned on at a speed of 50mm/s, acceleration of 50mm/s^2, within the range of 150mm÷300mm, lasting about 1.5h. Friction heat generated in the ball gear caused the screw thermal elongation. Then a series of measurements of positioning accuracy, distributed evenly over a period of 1.5h, was performed. During that time, the system was cooled by the natural heat exchange with the environment.

While the study, it was noted that the change of the temperature of the table, caused by the heat flow from the nut, causes a distortion of the measurement. Installing a sensor for the measurement of the table temperature allowed to introduce a correction based on the known thermal expansion coefficient, the measured geometrical dimensions and the recorded temperature.

4. EXPERIMENTAL VERIFICATION

For the purposes of verification, two measurement cycles lasting 6 and 3 hours respectively were carried out. In the first cycle, initially, the positioning accuracy of the machine being in a state of thermal equilibrium with the environment was measured. Subsequently, a cyclic movement of the table was turned on at a speed of 50mm/s, acceleration of 50mm/s^2, within the range of -150mm÷300mm, lasting about 1.5h. Then, 5 series of measurements of positioning accuracy were performed, evenly distributed within 1.5h. During this time, the system was cooled by the natural heat exchange with the environment. Next, the cyclic movement of the table was started again, this time within the range of 500mm÷650mm. And then 6 series of positioning accuracy measurements were performed. In total, when the first cycle was carried out, we performed 12 measurement series.

Selected measurements of positioning accuracy and the corresponding screw temperatures are shown in Fig. 6. and Fig. 7.

In the second measurement cycle lasting about 3h, initially, the positioning accuracy of the machine being in a state of thermal equilibrium with the environment was measured. Then, a cyclic movement of the table was turned on at a speed of 50mm/s^2, acceleration of 50mm/s, within the range of 300mm÷500mm lasting about 1.5h. Subsequently 5 series of measurements of positioning accuracy were performed, evenly distributed within 1.5h.

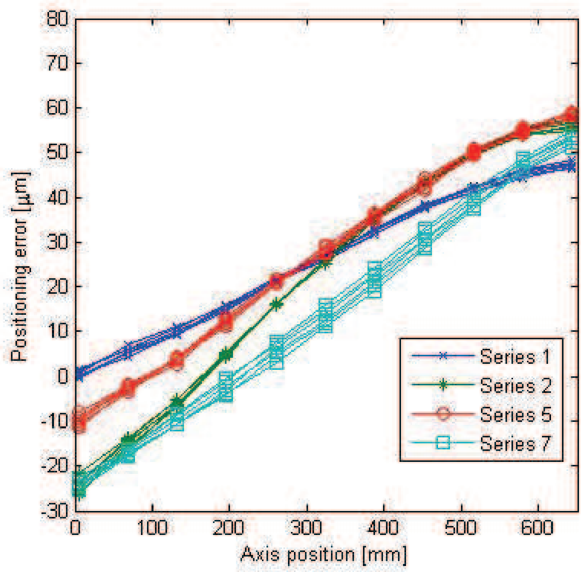

Fig. 6. Positioning error recorded during 1 measurement cycle

Error of the first measurement series (Fig. 6) performed in the conditions of thermal equilibrium with the environment shows that the screw was tensioned. This effect, as a geometric error, can be easily compensated. Due to the numerous literature concerning the subject [13, 14, 15], this issue was omitted in this paper.

Heating of the screw causes an increase in the inclination of the positioning inaccuracy curve, its distortion and vertical shift. This is caused by the non-linear screw temperature distribution and elastic flexibility of the angular bearings maintaining the screw.

Fig. 7. shows the temperatures recorded by the sensors placed in the screw during the performance of positioning accuracy measurements. Series 1 corresponds to the thermal equilibrium with the environment. Series 2 corresponds to the temperature distribution with the maximum value reached after the first heating of the screw. Series 7 corresponds to the distribution with a maximum temperature values, reached after the second heating of the screw. The temperature maxima correspond to the places where the nut slided during the cyclic movement. All data shown in Fig. 6., Fig. 7, Fig. 8. and Fig. 9. correspond to first cycle.

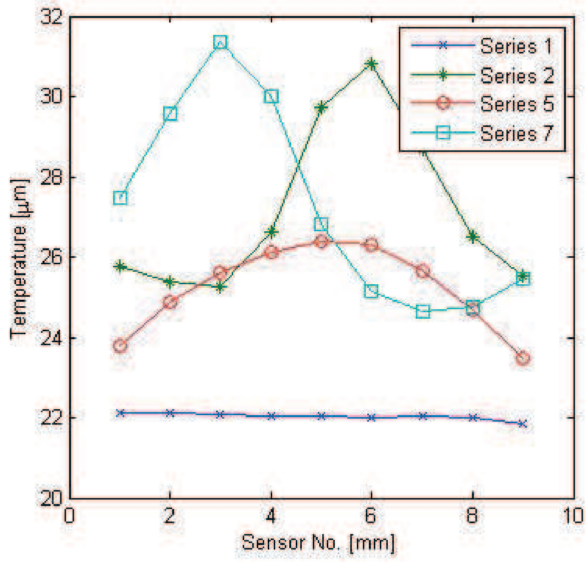

Fig. 7. Screw temperatures recorded during 1 measurement cycle

Calculation of the position correction (Fig. 8.) on the basis of the previously presented model allows for the compensation of the occurring thermal errors.

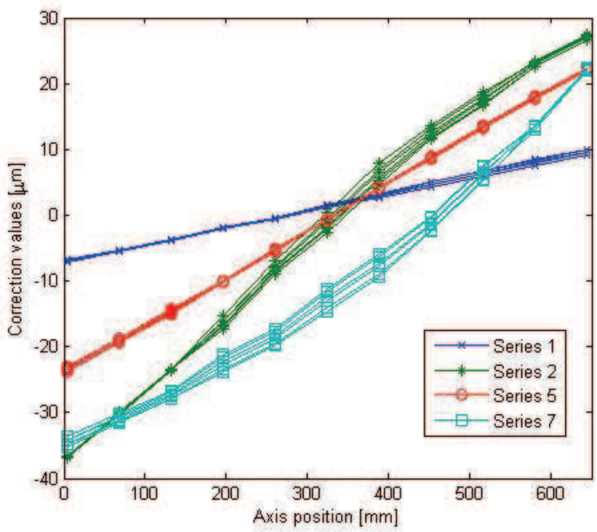

Fig. 8. Temperature corrections calculated for 1 measurement cycle

Application of the correction allows for a reduction of the thermal error from about 50µm to about 10µm (cf. Fig. 6 and Fig. 9). Further improvement of the positioning accuracy may be achieved easily by removing geometric errors.

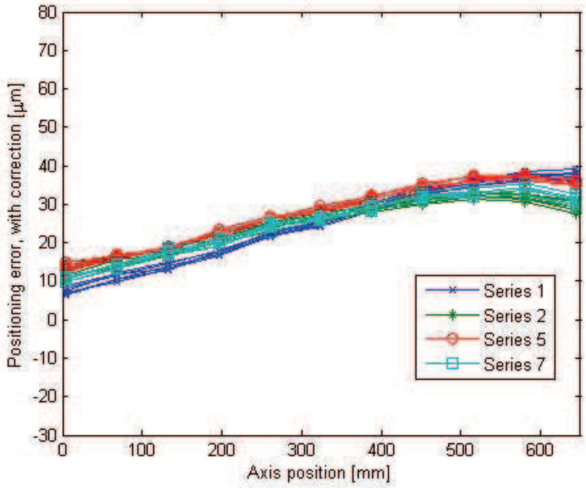

Fig. 9 Positioning error after the introduction of thermal errors during 1 measurement cycle

5. CONCLUSIONS

The application of the virtual axes architecture in the control system allows for freely correcting of the axis movement. It is possible to insert geometric errors correction and thermal error corrections into control system. Owing to the extensive literature in the subject of geometric errors, this issue was omitted in presented paper, focusing on the introduction of a on-line thermal error correction. In the presented example, the error connected with thermal deformation was reduced from about 50µm to about 10µm.

The proposed solution, owing to its accuracy, is close to the accuracy achieved by the solutions based on magnetic or optical scales (positioning accuracy at the level of ±2÷5µm [16]).

The target solution is to be 100% competitive and even better in terms of price than the solutions using linear encoders. It is believed that more accurate modelling of the thermal deformation error can be achieved by taking into account the characteristics of non-linear rigidity of the bearings. Due to time-consuming identification of the parameters of such a model, it may be advantageous to utilise neural networks to such a modelling.

The sensors installed in the screw can be used to monitor the work of the bearing nodes, whereas the calculated total elongation of the screw allows for the protection of the bearing nodes against excessive load as a result of strains introduced by thermal deformations.

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