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COMPENSATION OF THERMAL DEFORMATIONS OF THE FEED SCREW IN A CNC MACHINE TOOL

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Summary

The paper presents a novel system facilitating continuous compensation for thermal deformations of the feed screw during its work in the workshop conditions. Screw temperature measurement ensues in an automatic way and enables compensation of thermal deformations, and thus, the removal of one of the main components of thermal volumetric errors. NTC Sensors (thermistors) are situated along the screw. Data concerning the thermal state of the screw is used to determine thermal deformations by means of the analytic model. Quantitative determination of thermal deformations allows for the introduction of compensations in the control system of a CNC machine, increasing the accuracy of tool positioning in relation to the machined object.

Keywords: thermal error, compensation, feed screw, CNC machine tool

Kompensacja odkształceń cieplnych śruby napędowej w obrabiarce CNC

Streszczenie

W pracy przestawiono nowy układ prowadzący ciągłą kompensację odkształceń cieplnych śruby pociągowej podczas jej pracy w warunkach warsztatowych. Pomiar wartości temperatury śruby odbywa się w sposób automatyczny. Umożliwia kompensacje odkształceń cieplnych i tym samym usunięcie jednej z głównych składowych błędu – składowej cieplnej błędu wolumetrycznego. Czujniki rozmieszone są wzdłuż śruby. Wielkości określające stan cieplny śruby są stosowane do określenia odkształceń cieplnych za pomocą modelu analitycznego. Ilościowe wyznaczenie odkształceń cieplnych pozwala na wprowadzenie kompensacji w układzie sterowania obrabiarki CNC, zwiększającej dokładność pozycjonowania narzędzia względem przedmiotu obrabianego.

Słowa kluczowe: błąd cieplny, kompensacja, śruba toczna, obrabiarka CNC

Nomenclature

$\delta(x)$ – amendment compensating thermal deformations in the control system of a CNC machine

τ – the temperature excess over the reference temperature T_{ref}

T_{ref} – temperature for which positioning error was measured when the machine was in thermal equilibrium with the environment, ºC

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x – current position of the nut, mm
$T(x)$ – screw temperature in the function of distance, ºC
xi – location of the i^{th} temperature sensor in the machine axis system, mm
$T(xi)$ – temperature measured by the i^{th} sensor, ºC
α – thermal expansion coefficient, $\frac{\mu}{m \cdot °C}$

1. Introduction

The results of numerous experimental studies have shown that thermal deformations may be responsible for 40-70% of geometrical inaccuracies of machine tools [1]. The need to reduce the impact of heat generated in the operating machine on the machining accuracy, forced the implementation of thermally symmetrical machine design, the introduction of additional cooling systems [2] and systems of thermal deformation compensation [1, 3-5].

The last type of solutions is of particular interest to researchers, owing to its complementary role in relation to the other ones. Such an approach is advantageous, since materials with low thermal expansion coefficients are often too expensive and do not have adequate mechanical properties to serve as the primary material for the construction of machine tool assemblies. Complex cooling systems compared to the exact measurement of temperature occur to be economically uncompetitive, both at the stage of production and operation of the machine [6].

The development of thermal compensation experienced its peak along with the application of neural networks. Constantly decreasing cost of electronics and increase in its computational power enables the application and continuous improvement of algorithms which process the collected temperature data for the correction of location of the tool system in relation to the system of the machined workpiece [5, 7].

In the finishing machining process, where high precision of tool movement in relation to the machined workpiece is particularly required, the heat generated in a direct result of machining is removed along with the coolant and chips, thus has a relatively limited impact on the precision of machining [2]. The main sources of heat affecting the machining accuracy are then the systems of the main drive and the feed drive. For this reason, increased attention is paid to the phenomena occurring in the spindle bearing system and the drive transmission system: preloaded ball screw bearings, where there are significant places of heat generation from the perspective of occurrence of thermal errors.

2. Station Description

In order to investigate thermal deformations of the machine tool feed screw and develop efficient methods of their compensation, a special research station was proposed which copy the operation of a single table feed drive axis of a modern vertical CNC milling machine (Fig. 1).

In accordance with the prevailing trends the AC-SERWO drive was used, characterised by high efficiency, with an encoder mounted on the shaft, allowing for precise positioning. The applied ball screw comes from a commercially produced milling machine: AVIA VC 760. In order to eliminate backlash, the nut-screw connection is preloaded. The applied bearing units are original units from the AVIA VC 760 milling machine. The station enables the operation in the two configurations: with the preloaded ball screw (in order to increase its rigidity) and without the preload.

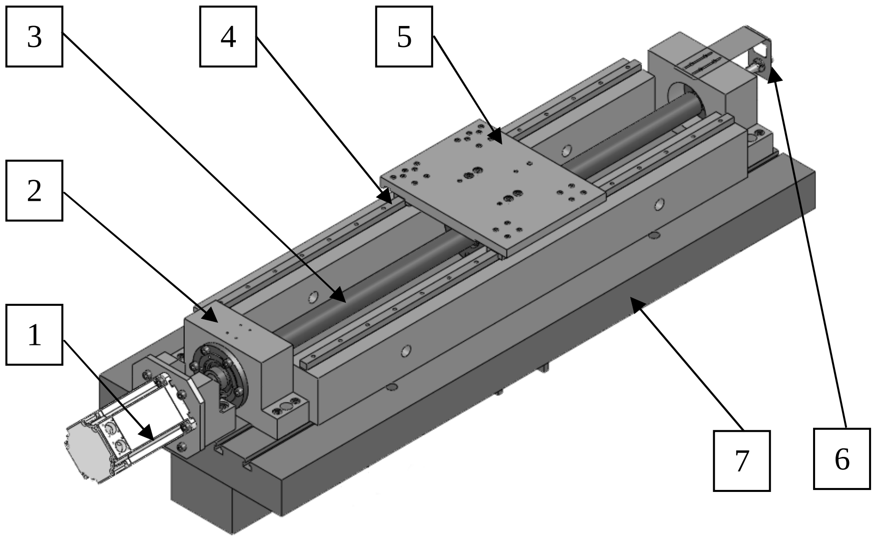

Fig. 1. Design of the research station for the measurement of the linear errors of a machine feed axis, caused by thermal deformations of the feed screw: 1 – engine, 2 – bearing support, 3 – ball screw with temperature sensors, 4 – linear guideway, 5 – movable table, 6 – electric rotary connector (slip ring), 7 – base

An axial borehole and a number of radial boreholes have been performed in the screw (Fig. 2). Negative temperature coefficient (NTC) resistors – temperature sensors have been installed in radial holes. Their wiring has been brought out through the axial borehole. In order to ensure the possibility of a free rotation of the screw, the sensors has been connected with a transduser device through a rotary electrical connector.

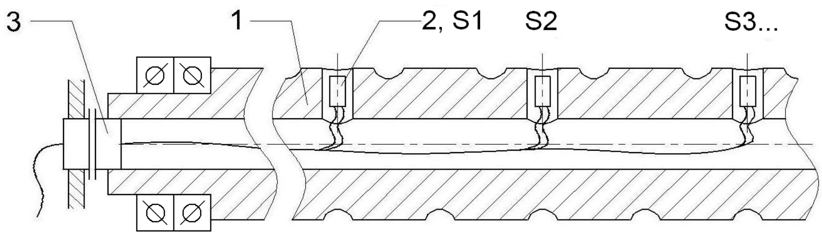

Fig. 2. Diagram of the assembly of temperature sensors in the feed screw: 1 – the screw, 2 – temperature sensors (S1–sensor 1, S2 – sensor), 3 – electric rotary connector

3. Dependence Model

Among the commonly used methods of modelling thermal deformations, the following ones should be highlighted: the finite element method, neural networks, polynomial regression models ARMA [8].

The method of finite elements is used for the initial design of machines [9], however, there are serious difficulties in ensuring the accuracy of the calculations [4, 10]. Moreover, the time-consuming character of calculation disqualifies its use for "on-line" compensation of thermal deformations in the model cooperating with the controller of a CNC machine tool.

Neural networks [11-15] may be characterised by dynamic properties and high-speed data processing, owing to the application of parallel processing. Furthermore, they enable to reduce the number of the necessary sensors installed in the machine. Unfortunately, their reliability in conditions different than the ones ensured during the network teaching is still in question.

The model enabling on-line compensation must be characterised with high computing speed, robustness and possibly high accuracy.

An analytical model was applied in the developed compensation system of feed screw thermal deformations. It uses a simple relationship between the screw temperature and its elongation. The function of screw temperature $T(x)$ along its axis has been interpolated with linear spline function. The value of the function is described with the relation (3.1). Function values in nodes – $T(xi)$ – correspond to the data recorded by temperature sensors:

$$T(x) = \frac{T(x_{i+1}) - T(x_i)}{x_{i+1} - x_i}(x - x_i) + T(x_i), \quad x \in (x_i; x_{i+1}) \qquad (3.1)$$

whereby:

$$\tau(x) = T(x) - T_{odn} \tag{3.2}$$

and

$$\delta(x) = \alpha \cdot \int_{0}^{P0} \tau(x)\mathrm{d}x \tag{3.3}$$

Such a model allows for the calculation of the correction δ(x) which, when included in the open control environment, will ensure the increase in the positioning accuracy. For the proper functioning of the correction in the control system it is necessary to provide an open control architecture using a virtual axis [12].

4. Measurements

To verify the efficiency of model functioning, an experiment was conducted, in which the station axis was heated with the use of cyclical movements of the table. Then, during the gradual cooling, measurements of screw deformation were gathered.

Thermal deformation of the feed screw was determined on the basis of the linear error measurement of the movable table, by means of a laser interferometer Renishaw XL-80 (Fig. 3).

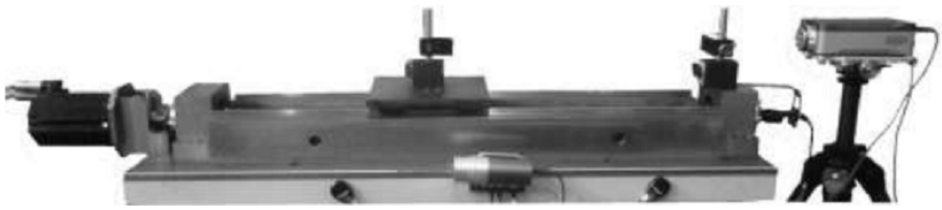

Fig. 3. Picture of the measurement position with the installed Renishaw set for the measurement of linear error

Exemplary data corroborating the effectiveness of the applied method has been presented in the charts below. Figure 4 presents the temperatures recorded during the conducted experiment by the NTC sensors situated inside the screw. In the heating phase (25-210 min) almost all temperatures rise exponentially, the exception is only the reading of the NTC0 sensor situated directly under the bearing unit. An analogous situation occurs in the cooling phase, where the temperatures also fall exponentially.

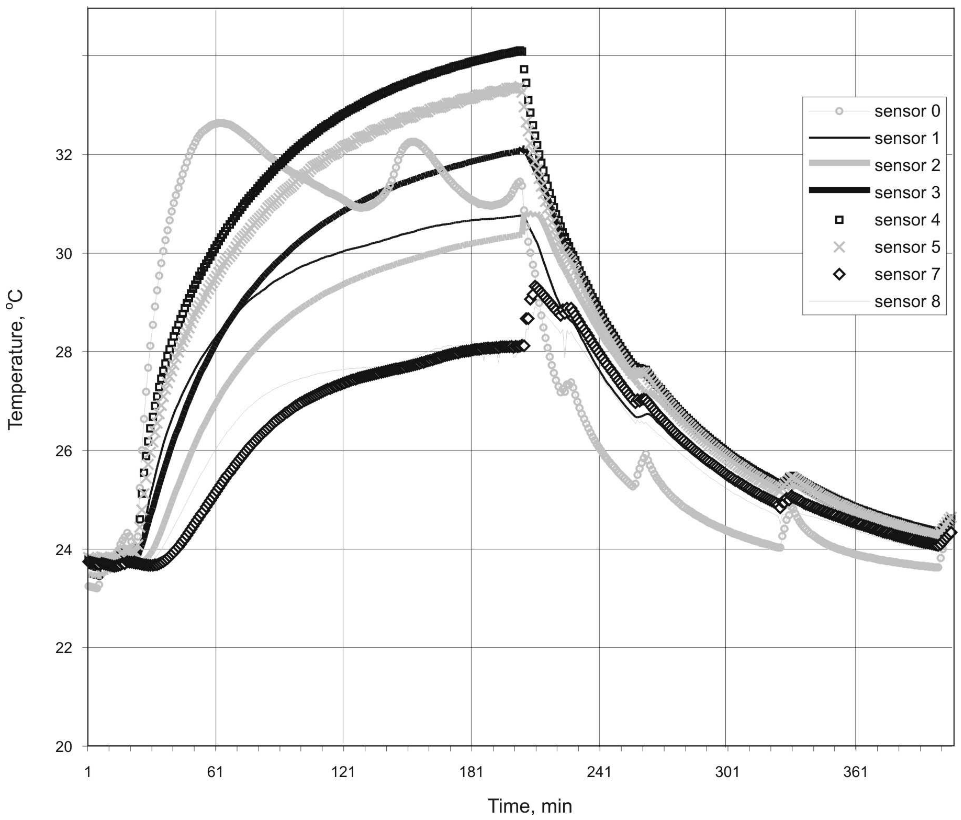

Fig. 4. Temperatures recorded during the experiment by the NTC resistance sensors situated in the feed screw. The rising edge corresponds to the collection of measurements of positioning accuracy

Since the linear error budget includes geometric errors originating form the manufacturing of the screw, guiding connections assembly, random error, engine encoder error as well as others, the assumed reference point was the linear error measured at the time when the machine was in thermal equilibrium with the environment ($T_{ambient} = T_{machine} = 22°C$)[1]

[1] The ISO-1 standard stipulates that all measurements should be performed in the temperature of 20°C or at least reduced by means of an appropriate correction (NDE) to such a form. ISO 230-3 slackens these requirements for the studies on the influence of thermal effects on the accuracy of positioning of machine axes.

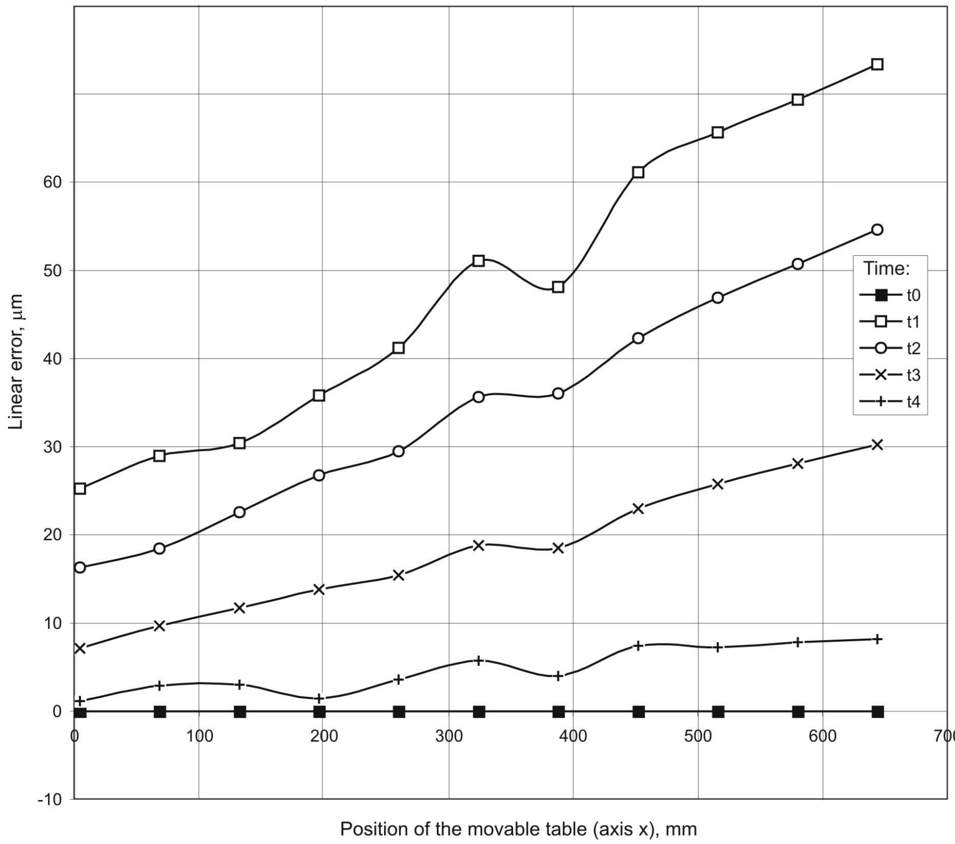

Fig. 5. The relationship between the positioning error, the table position and the temperature of the screw, without compensation

Linear error measurements were performed during convective cooling of the station. The collected data is presented in Fig. 5. It can be seen that with time the screw temperature decrease ($t0 < t4 < t3 < t2 < t1$), which causes a reduction of linear thermal error of the table driving axis.

Linear errors for a system with one floating bearing unit and one setting unit should decrease along with the closing of the table location to the setting unit. As can be seen in Fig. 5, along with the decrease of the x position, which corresponds to the approaching of the table to the setting unit, the positioning error is actually decreasing.

The calculated correction $\delta(x)$ allows for the reduction of linear thermal errors (Fig. 6). They residual error assumes a random character, which indicates proper elimination of the systematic component. The maximum value of the error recorded during the experiments has decreased from 73 µm to 13 µm. This confirms the effectiveness of the proposed method.

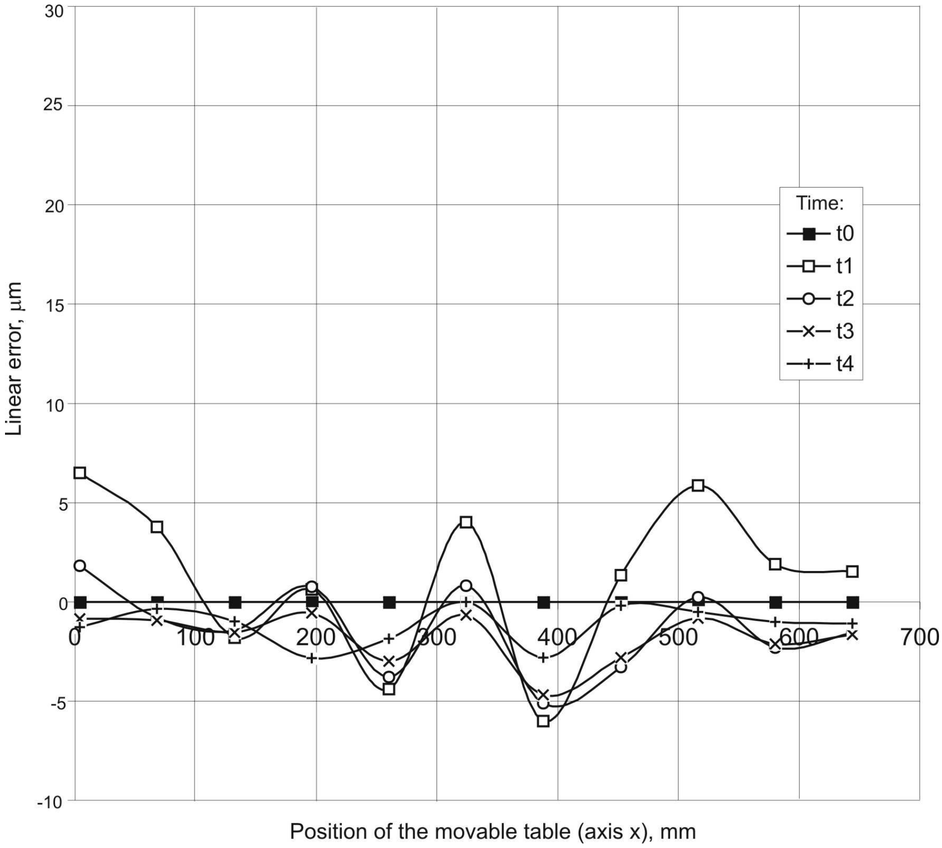

Fig. 6. The relationship between the positioning error, the table position and the temperature of the screw with the functioning compensation system

5. Conclusions

The proposed method allows for efficient reduction of linear thermal errors of the drive axis of the CNC machine. Positioning errors caused by thermal deformations of the screw have been reduced in the presented example by 80% (from 73 µm to 13 µm). Moreover, the developed method of compensation is characterised by much lower operating and implementation costs in comparison with the conventional cooling systems.

Acknowledgements

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