Thermal error compensation in CNC machine tools using measurement technologies

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Abstract. The required machining accuracy can be realized by compensating the thermal error of the machine tool. The paper presents a method of constructing a system of compensation for the thermal error of the machine tool. The method is based on the part measurement system installed on the machine. A review of studies in the field of precision machining was conducted. The review showed that the methods of correction of machining errors caused by dynamic and static factors using OMM-technology (On Machine Measurement) is presented in the literature. At the same time, the methods of compensation of the thermal error of machine tool built on the use of OMM-technology are poorly represented. Therefore, the practical implementation of control algorithms of the working bodies of the machine allowing one to compensate for its thermal error using OMM-technology is in demand. The methodology contains seven main stages, methodologically covering four areas of research. In addition to the experimental, mathematical and measurement areas of research, they also distinguish the area of software development (preparation of NC programs for CNC machines). It is proved that the presented methodology allows one to develop own automated system of compensation of a thermal error for any machine tool. It is shown that the most important directions of the framework for the improvement of the effectiveness of such system are to ensure the completeness of the experimental base and the accuracy of the adjustment of the thermal error compensation algorithms of the machine tool.

1. Introduction

One of the most important factors in ensuring the machining accuracy of CNC (Computer Numerical Control) machine tools operating at the maximum values of the equipment duty factor is the thermal deformation of the machine tool structure [1–4]. Despite the fact that in the past three decades, machine tools manufacturers paid great attention to the influence of thermal processes on machining accuracy, still the thermal errors of machine tools remain the most important component. For example, recent studies of thermal deformations of profile grinding machine tools have shown their significant influence on the accuracy of the wheels profile formation in X and Y directions [5]. When the excessive temperatures were about 12 °C , the maximum temperature displacements of the spindle in the Y-axis were about 42 μm. The survey of 55 manufacturers of machine tool equipment from 8 countries, including Japan, Germany and China and 20 machine tools consumers from Germany, showed the relevance of the thermal error in machine tools [6]. Despite the accumulated experience of the industry in relation to the thermal behavior of machine tools, the results of solving the problem of minimizing the thermal error in machine tools do not fully meet the requirements of production. In the survey there were small, medium-sized, large and very large enterprises. Their experience has shown that the thermal error in machine tools significantly exceeds the geometrical, static and dynamic errors. Even in the
conditions of modern high-tech production, thermal machining errors are the main factor for almost 50% of defective products. It is found that equally on the formation the production process, internal heat sources and the environment affect the formation of the temperature error of the machine tool. It is also found that the use of thermal stabilization systems in machine tools contradicts the energy efficiency issues. However, almost 75% of all companies prioritize process stability.

Modern CNC machine tools are equipped with various measuring systems that can be used to improve machining accuracy [7, 8]. The most widespread system installed on CNC machine tools is the part measurement system [9-13]. Intellectual using of such systems during machining allows you to significantly increase the machining accuracy without upgrades a CNC machine tool with additional error correction systems. This can significantly reduce the prime cost of production. So in [14], an ultra precision grinding machine was considered with a positioning accuracy of 100 nm (0.1 μm). Using the on-machine measurement (OMM) inspection system allowed for a triple correction profile aspherical surface. This approach led to a reduction in the machining error of the profile from 1867 nm to 177 nm. In [15], a methodology for ensuring the accuracy of contour milling of thin-walled parts is presented. And besides, machining of a turbine blade was carried out on a 5-axis machine vertical layout VMC-C30 with table B-axis and table C-axis. The test results demonstrated an opportunity to reduce the machining errors by at least 70% by using the OMM system.

Intelligent using of the error correction systems in the CNC machine assumes the implementation of special control algorithms for increased machining accuracy. These algorithms provide for changing the code of control programs for the CNC machines according to data from the OMM system. The methodology of error correction processing based on the OMM-technology is adequately reflected in the literature. But, issues of correction of the thermal error in the machine tools using the OMM-technology are poorly represented in the open press. Therefore, this work is devoted to the development of the methodology for the implementation of control algorithms for the machine tool operative parts for the thermal error compensation with OMM-technology.

2. Methodology description
2.1 The conditions for the implementation of the methodology
To implement OMM-technology in the control algorithms of the machine tool operative parts for correcting its thermal errors, the machine tool must be equipped with a measuring probe. But the measuring probe is not provided by a machine kitting. This is an available optional fitting-up for the overwhelming majority of CNC machine tools. A prerequisite for the implementation of this fitting-up is the presence of an unutilized controlled coordinate of the NC system. After installing the probe, it is necessary to calibrate it.

2.2 The content of the main stages of the methodology
The methodology includes seven stages. At stage one of the methodology, we prepare raw data by using the generation set of experimental thermal characteristics. At this stage, an analysis of the operating procedure of the manufacturing part is carried out and the basic diagrammatic work of equipment is formed.

At the second stage of the methodology, the construction of the predicted thermal displacements of the machine tool operative parts operating according to the diagrammatic work is carried out. This allows you to determine the corrective control actions for the machine tool operative parts.

Theoretical corrective actions are given as approximating functions [16]:

\[
\hat{\delta}_n(t_j) = \sum_{k=1,5,...,4m-3} x_{k,n} \left( 1 - e^{-(t_j-x_{k+3,j})/x_{k+3,n}} \right) + \sum_{k=1,5,...,4m-3} x_{k+2,n} e^{-(t_j-x_{k+3,j})/x_{k+3,n}}, \quad n \rightarrow X,Y,Z,  \quad (1)
\]

where \(x_{k,n}, x_{k+1,n}, x_{k+2,n}, x_{k+3,n}\) are the modal parameters, \(k\) is the indexing of the modal parameters, \(m\) is the number of temperature modes, \(t_j\) is the fixed moment of time at which measurements were
taken, \( \hat{\delta}_n(t_j) \) is the value of the thermal displacement along the \( n \)-th coordinate at the \( j \)-th instant of time.

The numerical values of the modal parameters are obtained using an automated system for calculating corrective actions (ASCCA). The ASCCA is implemented in MATLAB. The calculated values of displacements (1) determine the kind of changes in the diagrammatic work of the machine tool. These calculated values are associated with conducting current measurements with a measuring probe and the subsequent implementation of corrective actions. As a rule, this leads to an increase in the number and duration of each machining pass.

The third stage of the methodology is the adaptation of the CNC programs for a CNC machine tool for the implementation of thermal error correction. Adaptation of the CNC program consists in changing the program code by including two blocks: the block of the current coordinate correction along the Z axis and the account block of the intermediate measurement of the reference plane of the workpiece coordinate system. Changing the code of the NC program for a CNC machine tool is carried out manually, even if the control program can be written using a CAM system.

The fourth stage of the methodology is the first measurement of the reference plane during the machining of the workpiece. This position of along the Z axis is taken as a “zero”. All subsequent measurements, calculation, and implementation of corrective offsets of the operative parts of the machine tool are carried out relative to this level. Based on the results of this measurement, the preset position of the reference plane is clarified. Since the position of this surface may additionally change when the ambient temperature changes in the room with the installed machine tool. When measuring with a measuring probe, the relative position of the probe tip is transmitted to the CNC system as the resulting value along the Z axis.

The fifth stage of the methodology is the operational stage or the stage of the numerically controlled output. One of the important conditions for ensuring the machining accuracy is rigid adherence of the temperature mode or ambient temperature. When working out the NC (Numerical Control) program with corrective actions, the same temperature mode should be implemented, at which initial data were formed to determine the corrective actions (minor deviations are permissible).

The sixth stage of the methodology is a control operation performed on a stationary coordinate measuring machine. During this operation, a vector of measured dimensions \( \mathbf{P} \) is formed and compared with the given dimensions of parts \( \mathbf{T} \). If the machining error exceeds the dimension of the part drawing, the transition to the next decision block \( \mathbf{R} \) is performed. In this block, the possibility of continuing to manufacture the part is assessed or a decision is made to complete its machining due to irreparable errors.

The seventh stage of the methodology is modification of the NC program. The control program used in the methodology for a CNC machine tool has four fundamental differences from a typical program.

3. Results

The using in tests of the 3-axis machine tool is 400V (OOO «NPO «Stankostroenie», Russia). The measuring system installed on the machine tool is based on the TC50 measuring probe from Blum Novotest (Germany). The thermal characteristics of the machine tool can be constructed using the results of current measurements of the spindle head flange in the form of a «temperature displacement time» dependence \( \delta(t) \) along the corresponding X, Y or Z coordinate directions. In modern high-tech production, the thermal characteristics \( \delta(t) \) are based on measurements made directly on the machine tool using a measuring probe. The result of applying the methodology of correcting the thermal error of a machine tool is the correction of the displacements of the operative parts of a particular machine.

In this work, a series of experiments was additionally performed to compare the experimental data obtained with and without the probe. A series of experiments was carried out for different spindle rotational speeds. According to the general concept of the methodology, the experimental values of displacements were determined for the whole range of spindle rotational speeds with increments of 1000 rpm. The displacement values for intermediate rotational speeds were found from the approximation of the current discrete values. In this study, experiments were performed for five spindle speeds, which
were 1000, 2000, 3000, 4000, and 5000 rpm. At first, thermal characteristics were built according to the displacement values of the flange end of the spindle head of the machine along the Z axis. Measurements were carried out for 240 minutes with a time interval from 5 to 20 minutes. Smaller interval values were used for the first hour of measurement. Figure 1a shows the results of a series of experiments at idle pass for five spindle speeds: 1000, 2000, 3000, 4000, and 5000 rpm. The family of experimental characteristics \( \delta(n) \) were organized for two values of the initial temperatures (within \( 3 \, ^\circ C \)) and ten machine operating times as follows: 10, 20, 30, 40, 50, 60, 80, 120, 180, 240 minutes. The curves are numbered from 1\((1')\) to 10\((10')\). An analysis of the experimental characteristics showed that for different values of the initial temperatures, a variation of experimental data was observed within 8 \( \mu m \).

The convergence of measurement results obtained by two measurement methods (with and without the measuring probe) is illustrated in Figure 1b. The characteristics \( \delta(t) \) from 1 to 5 represent the measured displacements of the end face of the spindle head for five spindle speeds. The \( \delta(t) \) characteristics from 1' to 5' are obtained from measurements of the reference plane of the part using the TC50 probe. The maximum discrepancy of the corresponding data did not exceed 8 \( \mu m \) or not more than 10% of the maximum displacements at the working spindle speed. This means that the raw data in the form of a set of experimental values of displacements can be formed by any of the considered methods, since their reliability is comparable.

![Figure 1. The experimental thermal characteristics](image)

To confirm the effectiveness of the developed methodology and algorithms for correcting the thermal error of a CNC machine tool, the experiment was conducted using a premachined part with a stepped surface. The relative step height was 0.5 mm, the step width was 5 mm. The stepped surface allows end milling to be performed most accurately and conveniently at individual points in time with a predetermined time interval. Previous experiments for this machine tool showed that a time interval of 20 minutes provides a noticeable change in the thermal error of the machine tool, exceeding the measurement error.

To estimate the thermal error of the machine tool that changes in time, six surfaces were milled across the stepped surface (Figure 2a). The basic milling depth prescribed in the NC program at each step was also 0.5 mm (without taking into account the values of both correction and thermal error).

The first transverse stepped surface was taken as the surface with perfect dimensions. This is explained by the fact that the surface machining took 20 seconds - during this time the thermal error did not have time to form. The second transverse stepped surface was formed taking into account the formation of thermal error. During the formation of this surface, a time delay was used before milling each step equal to 20 minutes. The time delay allowed one to form the amount of thermal displacements of the operative parts of the machine tool. The following stepped surfaces were formed taking into account the correction of the machine tool thermal error. They were formed similarly to the second surface, but for different temperature conditions of the experiment. The peculiarity of the formation of the sixth surface was the fact that before the sixth surface was machined, the position of the reference plane was corrected using a measuring probe. The experiment was conducted on different days with
slightly different temperature conditions. Therefore, the discrepancy between the experimental data for the steps from the third to the sixth did not exceed 5 μm. Control measurements of machined surfaces, carried out on the Wenzel XOrbit 55 coordinate measuring machine, showed that the discrepancy of the experimental data did not exceed 3 μm.

To illustrate the effectiveness of the proposed methodology and the developed algorithms for correcting the thermal error of the machine tool the results of measurements performed on three surfaces in the direction of the y axis are presented in Figure 2b. The curves presented in Figure 2b are formed by connecting separate points with segments. The first curve is formed from the measurement results of the first surface. Curve 2 is formed according to the results of measurements of the second surface in the last time interval of the test with the maximum thermal error. Curve 3 represents the result of measuring the third surface obtained by implementing the algorithms of the thermal error correction of the machine tool.

4. Discussion.

To eliminate possible measurement errors when using a measuring probe due to incorrect operation of the measuring apparatus, the NC program must include a module for checking the measured data. This NC program includes five blocks [17]. The idea of the module is to use not one, but several repetitive measurements. This makes it possible to exclude the use of an erroneous measurement value in correction algorithms. The duration of one repeated measurement is no more than 3 s.

A specific feature of the measuring cycles for the TC50 Series probes is the use of predefined user variables. For example, for Sinumerik CNC systems, they are stored in the area reserved for R-parameters. In this methodology, the measured value along the Z axis is stored in the parameter “R [02]”.

The implementation of OMM-technology in the machining can be carried out without the use of predictive models. In this case, another algorithm is implemented for generating corrective actions of the machine tool thermal error. Corrective actions are carried out on the basis of only measurement results without predicted values of thermal displacements of the operative parts of the machine tool.

In the discussion, I would like to highlight some of the features of the final stage of the proposed method - this is a modification of the NC program. The NC program used in the method for a CNC machine tool has four principal differences from the typical program.

The first difference. The number of part of the operating cycles is greater than that in a typical NC program, since in this case the measuring cycles are added. The number of measuring cycles is determined by the predicted intensity of the machine tool thermal error.

The second difference. Corrective offsets of the operative parts of the machine tool are performed subject to restrictions:
\[ \Delta \leq \varepsilon , \]  

where \( \Delta \) is the measured error (module), \( \mu m \); \( \varepsilon \) is size tolerance set by machining technology, \( \mu m \).

If condition (2) is not satisfied, the machining is completed due to the formation of a reject.

Not to receive a reject, the limit value of the thermal error \( \varepsilon' \) should be set slightly less than the scope tolerance value:

\[ \varepsilon' = k \cdot \varepsilon , \quad k \Rightarrow [0, 1] , \]  

where \( k \) is safety factor.

The third difference. The NC program for a CNC machine tool is implemented by two nested loops. The external loop is determined by the machining passes provided by the machining technology and by additional passes conditioned by the result of the working of the ASCCA [17]. Inner loops describe machining a part without measurement, subject to the conditions:

\[ \Delta_{giv} \leq \varepsilon' , \]  

where \( \Delta_{giv} \) is the predicted value of the machine tool thermal error.

In this case, the execution of the corrective actions by the machine tool operative parts is carried out within the inner loop.

The fourth difference. The algorithm for correction of the machine tool thermal error includes an additional block «Recalculation of correction», in which automatic recalculation of corrective actions is performed. For example, during the execution of an internal loop, corrective actions of type (1) are implemented, leading to some predicted value of the error \( \Delta_{giv} \). At the same time, as a result of the measurement, the deviation of the actual thermal error of the machine tool from the predicted one is inevitably fixed:

\[ \beta = |\Delta_{giv} - \Delta| , \]  

where \( \beta \) is the discrepancy between the two errors, \( \Delta \) is the actual error.

In the «Recalculation of correction» block, in order to eliminate the detected discrepancy of two errors \( \beta \), recalculation of corrective actions at the current time is performed.

Analysis of the measurement results (Figure 2b) showed that after 240 minutes of heating the machine tool, the temperature error was about 37 \( \mu m \) (measurements were performed on a coordinate measuring machine) and 39 \( \mu m \) (measurements were performed on a machine using a measuring probe). The use of thermal error correction algorithms made it possible to reduce it to almost 10 \( \mu m \). For more accurate machining, more precise adjustment of the correction algorithms was required, for example, by introducing additional measurement passes during machining.

5. Conclusion
In this study, the methodology was presented for the practical implementation of thermal error compensation algorithms for CNC machine tools. The methodology contains seven main stages and covers four areas of work. The experimental area is associated with the formation of the raw data. Software is associated with the approximation of experimental characteristics. The measurement area is associated with the implementation of measurements directly on the machine tool. The operational area is related to the development of NC programs for CNC machine tools that implement OMM-technologies and thermal error correction algorithms.
It has been proven that the presented methodology allows developing an individual automated system for compensating the resulting thermal error for any machine tool. The most important factors of the effectiveness of the developed methodology are the completeness of the experimental base and the accuracy of tuning the thermal error correction algorithms.

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