Experimental research of kinetic and dynamic characteristics of temperature movements of machines

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Abstract. Nowadays, the urgency of informational support of machines at different stages of their life cycle is increasing in the form of various experimental characteristics that determine the criteria for working capacity. The effectiveness of forming the base of experimental characteristics of machines is related directly to the duration of their field tests. In this research, the authors consider a new technique that allows reducing the duration of full-scale testing of machines by 30%. To this end, three new indicator coefficients were calculated in real time to determine the moments corresponding to the characteristic points. In the work, new terms for thermal characteristics of machine tools are introduced: kinetic and dynamic characteristics of the temperature movements of the machine. This allow taking into account not only the experimental values for the temperature displacements of the elements of the carrier system of the machine, but also their derivatives up to the third order, inclusively. The work is based on experimental data obtained in the course of full-scale thermal tests of a drilling-milling and boring CNC machine.

1. Introduction

The analysis of works in the field of thermal deformations of metal-cutting machine tools for the last decades has shown that success in increasing the heat resistance of CNC machines does not have a global character [1-3]. Such leaders of the market as OKUMA, Kitamura, Mitsubishi have their own automated systems for thermostabilization and correction of the temperature error of machines, which, when they work together, lead to sufficient heat resistance of the vendor data machines. To build a global approach to solving the problem of the thermal stability of machine tools, it is necessary to find solutions of a number of fundamental problems, both in the field of heat generation in sources and in its propagation. This leads to the need for the creation of automated systems of thermal stability or thermal compensation to perform thermal tests of specific machines for the formation of a database of appropriate thermal characteristics [3-8]. In this research, the author define thermal characteristics of machines as the functional dependencies of temperature, temperature displacements of the elements of the carrier system of the machine and their derivatives of the first, second and third orders on time [9].

Thermal testing of machines is relatively time-consuming and is determined by the time period over which the information on the thermal characteristics of the machine is collected in sufficient quantities. The previously proposed method for determining the time of the termination of thermal tests [9], based on an analysis of the derivatives up to the third order inclusive, did not affect the study of the temperature displacements of machines. There is a linear relationship between displacements and temperature for bodies of simple form, as evidenced by the theory of elasticity. For the carrier
system of the machine, this relationship is more complex. This is due to the fact that the temperature movements of the machine form its final processing precision. In this research, let us present the results of related to the improvement of the methods, which are creation of additional tools for determining the time of completion of full-scale testing of the machine.

2. Materials and methods

First of all, let us define the terms used in the study. By the kinetic characteristics of the temperature displacements of the machine, the authors mean the rate of change in the temperature displacements $VZ(t)$. Under the dynamic characteristics, acceleration and sharpness of the changes in the temperature displacements $AZ(t)$ and $RZ(t)$, respectively.

As the object of experimental research, drilling-milling and boring CNC machine 400V manufactured by LLC SPO Stankostroenie was chosen. As measuring equipment for the conducted thermal tests, the authors use digital multichannel temperature meter MIT-12TP-11, multi-turn indicator heads of MIG type (GOST 9696-75) of accuracy class 0 and measuring probe TC 50 from Blum-Novotest Gmbh (Germany) [10]. Temperature measurements were carried out at twelve points of the machine carrier system. To increase the accuracy of the conducted experimental investigations, all the measurements were carried out consistently in three coordinate directions along the X, Y, and Z axes. Also the measurements were carried out under the following operating conditions of the spindle unit: 1000, 3000 and 5000 revolutions per minute. In all modes, the maximum values of the temperature movements were fixed along the Z axis.

Figure 1. Typical graphs of temperature displacements $Z(t)$, speed $VZ(t)$, acceleration $AZ(t)$ and sharpness $RZ(t)$ of temperature changes versus time

Figure 1 shows the typical results of measuring temperature displacements $Z(t)$ and their time derivatives - velocity $VZ(t)$, acceleration $AZ(t)$ and sharpness $RZ(t)$ obtained for the spindle speed of 5000 rpm. In accordance with the developed methodology [9] in Figure 1, the numerals denote the characteristic moments of the time of the proceeding processes. Point 1 determines the maximum speed and the zero acceleration of the change in temperature displacements. Point 2 determines the minimum of acceleration, zero sharpness of change of temperature displacements. Point 3 determines the maximum of sharpness, the kink on the curve of the acceleration of the change in temperature displacements. Point 4 determines zero value of sharpness and bend on the curve of acceleration of change of temperature displacements.

According to the developed method [9], the specific points of the experimental characteristics are revealed first by the characteristics corresponding to higher orders of the derivatives. In this research, the authors proposed introducing a normalized indicator of all characteristic points for a more accurate fixation of characteristic points. All listed points were calculated by the formula:
\[ K_{\text{var}}(t_i) = \left[ K_{v/a}(t_i) + K_{a/r}(t_i) \right] / K_{\text{max var}}, \]  

where \( K_{v/a}(t_i) \) - speed-acceleration coefficient used to determine the position of point 1; \( K_{a/r}(t_i) \) - acceleration-sharpness indicator used to determine the position of points 2 and 4; \( K_{\text{max var}} \) - maximum value of the indicator coefficient.

The speed-acceleration coefficient and the acceleration-sharpness coefficient are calculated by the following formulas:

\[ K_{v/a}(t_i) = |VZ_i(t_i)| / |AZ_i(t_i)|, \]  
\[ K_{a/r}(t_i) = |AZ_i(t_i)| / |RZ_i(t_i)|, \]

where \( |VZ_i(t_i)| \) - absolute value of the rate of change of movement at the i-th time moment; \( |AZ_i(t_i)| \) - absolute value of the rate of change of movement at the i-th time moment; \( |RZ_i(t_i)| \) - absolute value of the sharpness of the movement change at the i-th time moment.

**Figure 2.** A typical graph of the indicator coefficient of all characteristic points \( K_{\text{var}}(t_i) \)

Figure 2 shows a typical graph based on the results of calculating the above-mentioned indicator coefficient. The first two peaks on the obtained graph with a high degree of accuracy identify characteristic points 1 and 2, described in the characteristics of temperature displacements \( Z(t) \), \( VZ(t) \), \( AZ(t) \) and \( RZ(t) \). The position of point 4, obtained from the calculation of the indicator coefficient of all characteristic points, gives a value with a relatively small error for the actual experiment. The position of point 4 determines the time of completion of the full-scale experiment. The error fixed in this experiment did not exceed 15 minutes - this is the manifestation of the sensitivity of the experimental values for the characteristics constructed from the derivatives. Analysis of the graph (Figure 2) also showed that the accepted indicator coefficient of all characteristic points does not allow us to determine the position of characteristic point 3. In the first works on the method of reduced thermal tests of machines, the construction of thermal characteristics was limited to the use of second-order derivatives [9]. Therefore, the position of characteristic point 3 was particularly important since its position was associated with the time of the termination of the thermal tests. But if it is possible to
determine point 4, the practical value of this point has significantly decreased. The remaining peaks in the indicator-coefficient graph appearing after the 300th minute represent some periodic fluctuations, which indicate the onset of the stabilization process of temperature displacements.

Using the introduced indicator coefficient of all characteristic points and the experimental data obtained, let us determine the time of the onset of the temperature stabilization and the value of the stabilized temperature displacement. Let us assume that in the first approximation, temperature displacements $Z(t)$ in the region from point 4 and the time instant until the time of the onset of the temperature stabilization are described by the function:

$$Z(t) = Z(t_4) + VZ(t_4) \times t_{\text{stop}} + AZ(t_4) \times t_{\text{stop}}^2 / 2,$$

where $Z(t_4)$ - value of temperature displacement at time $t_4$; $VZ(t_4)$ - value of the speed of movement at point 4 at time $t_4$; $AZ(t_4)$ - value of the acceleration of displacement at point 4 at time point $t_4$; $t_{\text{stop}}$ - remaining value of the time before the onset of the moment of stabilization of temperature displacements.

Let us assume that when the time of stabilization of temperature $t_{\text{st}}$ displacements arrives, the rate of temperature displacements $VZ(t_{\text{st}})$ must be zero. The acceleration throughout the considered time interval is constant; then let us obtain the relation:

$$VZ(t_{\text{st}}) = VZ(t_4) + AZ(t_4) \times t_{\text{rem}}$$

or

$$VZ(t_4) + AZ(t_4) \times t_{\text{rem}} = 0.$$

This allows one to determine the value of the time remaining until the start of the process of stabilization of temperature movements:

$$t_{\text{rem}} = VZ(t_4) / |AZ(t_4)|.$$

Adding the estimated residual time, determined by formula (7), to the value of time at point 4, let us determine the total time until the moment of the beginning of the process of stabilization of temperature displacements:

$$t_{\text{st}} = t_4 + t_{\text{rem}}.$$

Using the proposed indicator coefficient of all characteristic points makes it possible to shorten the time for performing full-scale thermal tests of machines and other complex systems. In the experiment considered, the duration of the thermal tests of the machine at one fixed spindle frequency was 250 minutes. Using the coefficient-indicator of all characteristic points showed that the position of characteristic point 4 is determined on the 175th minute. Thus, the shortening of the duration of full-scale tests will be 30%, which at a high cost of a modern machining center is especially urgent.

The revealed regularities were confirmed by processing the entire set of experimental data on the temperature displacements obtained in the above-mentioned operating modes of the machine. Figure 3 shows graphs of the indicator coefficients of all characteristic points obtained at different seasonal times and for different rotational speeds of the spindle.

The conducted research allowed one to formulate the conclusion that the construction of graphs of the indicator coefficients for the characteristics of the temperature movements of the machine, corresponding to small spindle rotational frequencies, fixes all the specific points in the form of the first peak values. An increase in the spindle rotation frequency leads to the fact that the third characteristic point becomes little informative for the introduced indicator coefficient of all characteristic points. With an increase in the spindle rotation frequency, the graphs of the indicator...
coefficients of all characteristic points (Figure 3) show a shift to the left of the position of the fourth characteristic point. This confirms the fact that the time of the temperature stabilization of the carrier system of the machine from the frequency of rotation of the spindle is known from the actual experiments.

**Figure 3.** Typical graphs of the indicator coefficients of all characteristic points $K_{i/o}(t_i)$

**Table 1.** The results of the experiment and calculation of the indicator coefficients

| Characteristic points | $t_i$, min | $Z(t_i)$, µm | $VZ(t_i)$, µm/min | $AZ(t_i)$, µm/min$^2$ | $RZ(t_i)$, µm/min$^3$ | $K_{i/o}(t_i)$ | $K_{i/r}(t_i)$ |
|-----------------------|------------|--------------|--------------------|------------------------|------------------------|---------------|---------------|
| 0.000                 | 14.545     | 12.734       | 0.927              | 0.00383                | -6.79E-04             | 241.956       | 5.638         |
| 1                     | 19.394     | 17.270       | **0.937**          | **8.82E-04**           | -5.47E-04             | **1062.431**  | 1.614         |
|                       | 24.242     | 21.823       | 0.935              | -0.00147              | -4.32E-04             | 636.224       | 3.401         |
|                       | 53.333     | 47.184       | 0.781              | -0.00716              | -3.32E-05             | 109.013       | 215.680       |
| 2                     | 58.182     | 50.884       | 0.745              | -0.00713              | -1.84E-06             | 103.107       | **3924.080**  |
|                       | 63.030     | 54.413       | 0.710              | -0.00717              | 2.26E-05              | 99.078        | 317.829       |
|                       | 82.424     | 66.884       | 0.579              | -0.00617              | 6.83E-05              | 93.916        | 90.391        |
| 3                     | 87.273     | 69.621       | 0.550              | -0.00583              | **7.05E-05**          | 94.405        | 82.751        |
|                       | 92.121     | 72.221       | 0.523              | -0.00548              | 7.02E-05              | 95.431        | 78.050        |
|                       | 169.697    | 100.419      | 0.237              | -0.00288              | 4.33E-06              | 82.243        | 664.818       |
| 4                     | 174.545    | 101.533      | 0.223              | -0.00286              | 3.93E-06              | 77.951        | **728.436**   |
|                       | 179.394    | 102.580      | 0.209              | -0.00284              | 4.11E-06              | 73.630        | 690.551       |
|                       | 252.121    | 110.893      | 0.035              | -0.00155              | 3.18E-05              | 22.755        | 48.786        |

The full table of experimental results are presented in [11].

The carried out researches allowed one to single out the main stages of the methodology of using the indicator coefficients, built on the basis of the kinetic and dynamic characteristics of the
temperature movements of the machine.

The first step is formation of the base of experimental data of temperature displacements for different rotational speeds of the spindle.

The second step is processing of experimental data - smoothing the experimental data, that is, finding the best approximating dependencies for the characteristics of the temperature movements of the machine. At the same step, the kinetic and dynamic characteristics of the temperature displacements of the machines are formed.

At the third step there was calculation of the corresponding speed-acceleration and acceleration-sharpness indicators and plotting the dependency curves of the indicator coefficients of all points.

At the fourth step there was analysis and decision-making on the duration of full-scale tests. When constructing a graph of the dependencies of the indicator of all characteristic points in real time, considerable time-saving of field tests should be expected. When constructing such graph using the results of the full experiment, it is possible to obtain an estimate of the stabilization time of the temperature displacements of the machine.

3. Conclusion

Thus, based on the studies conducted, the following conclusions can be formulated:
- the introduced indicator coefficient of all characteristic points allows the position of a specific point to determine the moment of completion of the full-scale experiment to be determined with high accuracy;
- calculation of the values of this indicator in real time allows a 30% reduction in the duration of full-scale tests of the machine while forming a database of experimental characteristics.

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