Influence of thermo-mechanical deformations on the positioning accuracy of CNC machine tools

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Abstract: This research aims at improving the machining accuracy of the CNC machine tools by decreasing the errors caused by the thermo-mechanical deformations and increasing the positioning accuracy of the mobile element. This work analyses and researches the effects of the thermo-mechanical deformation on the positioning accuracy of the feed kinematical linkages of the CNC machine tools that are using the indirect measuring system of the position. The analysis is focused on feed kinematical linkages having rapid speed rates, of 40 m/min, that use a preloaded bearing system of the ball screw, supported at both ends. Constructive methods are also presented for decreasing the temperature at the heat generating sources by thermo-stating both the ball screw and its bearings. Through thermostats the temperature in the ball screw and its bearings is decreased, that leads to decreasing its influence on the positioning accuracy. The thermo-stating of the ball screw makes possible to keep a constant preloading force of the two ball screw nuts and, as far as the bearings are concerned, the coolant agent is the same as the lubrication agent that leads to a smooth running and, by default, to expanding the life of the feed kinematical linkage.

1. Introduction
The CNC manufacturing industry is facing a quite strong competition that determines the CNC machine tool builders to get adapted to the new requirements through an increased care, both in design/constructive terms and economically, without neglecting the high accuracy, repeatability and productivity. Accuracy represents the most important feature of the CNC machine tools that finally is reflected into the quality of the surfaces being processed through cutting. For this reason, the CNC machine tool builders are struggling to improve the accuracy through various methods, through design or software solutions at lower costs. In order to obtain a cutting accuracy as good as possible on the CNC machine tools it is necessary the positioning errors to be as low as possible, especially when the measuring system of the machine is of indirect type. The accuracy of a machine tool is directly influenced by the geometry errors, kinematical, dynamical errors and thermo-mechanical errors, too [1]. Out of the total number of CNC machine tools the errors caused by thermo-mechanical deformations have a relevant percentage, whose range is 40-70%, according to the statistics of the researchers in this domain [2-5]. The thermo-mechanical deformations of the CNC machine tools are caused by internal and external heat sources. The external sources consist of the temperature variations from day to night, season to season or other machine tools working nearby. These can be controlled through a monitored working environment. The internal heat sources that cause thermo-mechanical deformations consist of the electric motors on the machine, contact between tool and work piece
during the cutting process and especially of the friction between the components of the kinematical linkages. The heat sources consisting of the friction between the kinematical linkage components can be found into the slide-guideway system, as well as into the ball screw bearings and ball screw - nut mechanism. According to the research carried out by the ball screw manufacturer Gamfior (Italy) it resulted that each increase by one degree Celsius above the temperature of $20^\circ$ C leads to an axial deformation of the ball screw by $0.01 \text{ mm/degree}$ [6]. An important role in assessing the influence of the thermo-mechanical deformations upon the positioning accuracy of the moving element is held by the measuring system being used by the feed kinematical linkage that can be of direct or indirect type. In case of direct measurement the position encoder will directly measure the location of the moving element; this measurement system has the capacity to automatically compensate the errors caused by the thermo-mechanical deformations. In order to get more accurate value of the location, the position linear encoders have to be made of materials that are not affected by temperature variations or, at any event, that can be cooled by air or liquid, because, otherwise, the thermal transfer from the machine tool to the measuring system will have a negative impact upon the measurement accuracy. The direct type measuring systems are costly; therefore, the indirect type systems with rotary encoders are used. These can be usually mounted on one of the intermediary elements of the kinematical linkage. In this case, all elements of the kinematical linkage structure, from the place where the rotary encoder is located, up to the final element that is the slide, must be manufactured with a high accuracy, because the errors on this portion of the kinematical linkage cannot be compensated by the position canned cycle. Negative effects in case of the indirect measurement can also be recorded when thermo-mechanical deformations come up; these cannot be compensated through the position canned cycle and for this reason design solutions need to be found in order to keep under control the errors caused by the thermo-mechanical deformations.

2. Solutions for compensating the thermo-mechanical deformations

In order to lower the value of the thermo-mechanical deformations various design solutions are being used. One of them consists of preloading the ball screw while mounting it into bearings, by a force that would correspond to the value of the axial deformation $\Delta_t$ equal to the value of the sequent thermo-mechanical deformation $\Delta_{it}$ at stabilised duty, according to equations (1) and (2):

$$\Delta_{it} = L \alpha \Delta_t \cdot 10^3$$  \hspace{1cm} (1)

The symbols mean: $L$- length of the ball screw; $\alpha$- coefficient of thermal dilatation; $\Delta_t$- temperature variation. As such the value of the preloading force $F_p$ of the ball screw will be determined according to equation (3):

$$\Delta_{it} = \frac{F_p L \cdot 10^3}{EA}$$ \hspace{1cm} (2)

$$F_p = \frac{\Delta_t E A}{L \cdot 10^3}$$ \hspace{1cm} (3)

Where: $E$- elasticity module of the steel of which the ball screw is made; $A$- rated surface of the ball screw cross section. With the use of this solution on a machine tool when it reaches the stabilised duty, the preloading force $F_p$ in the ball screw will be annulled ($F_p = 0$) [7]. This solution is used at a low extent by the machine tool builders because the settling of the stabilised working duty may be construed differently because of the cutting duties that may vary a lot during the 8 hours time of the machine running. Some researchers are using methods based on prediction and compensation of errors caused by thermo-mechanical deformations in order to improve the positioning accuracy [8]. An innovative method consists of decreasing the thermo-mechanical deformations at the source through a thermostatic system that may have a positive effect on the positioning accuracy. Such a solution will be presented in this work.
3. Innovative solution to compensate the thermo-mechanical deformations at the source

Through the thermostatic method of the ball screw and its bearings, the temperature resulting from the friction between the components of these subassemblies will be lowered and the thermo-mechanical deformations will decrease, thus leading to the improvement of the positioning accuracy on the translation axes of the CNC machine.

Figure 1. Thermostat system of the ball screw and its bearings.

Figure 1 shows the thermostatic system of a ball screw. This system has a double role: the first one is to bring the machine tool faster to the preheating stage and to the stabilised running duty, in order to save time and to lower the energy costs. The second role is to keep an optimal, constant temperature of 21°C during the entire running time of the machine. Practically, the errors caused by the thermo-mechanical deformations will be very low and the coolant agent which is the same as the lubrication agent used for bearings will keep a constant viscosity of the lubricant. Viscosity \( \rho \) decreases very much along with the temperature increase, as per the equation (4), and affects the carrying capacity of the lubricating oil that will lead to higher friction and wear into the bearings of the ball screw.

\[
\rho = \rho_0 e^{-\beta(t-t_0)}
\]  

(4)

The symbols mean: \( \rho \)- lubricant viscosity; \( \rho_0 \)- viscosity corresponding to the initial temperature \( t_0 \); \( \beta \)- constant in function of temperature (at \( t_0 = 21 ^\circ C \) it will correspond \( \beta = 0.00124 \) in case of industrial lubricants).

The functioning mode of the thermostatic system consists of performing a closed hydraulic circuit, where the coolant goes out from the hydraulic group 2 and enters the left side bearing 4 of the ball screw 3, then it flows through the inner bore \( \phi 20 \text{ mm} \) drilled along the ball screw and finally it enters the right side bearing 5 thus finishing the process of temperature take-over. Subsequently the heated coolant will be cooled into the Freon unit 1.

The method of thermostatic control at the source consists of drilling an inner bore on the entire length of the ball screw, through which the coolant that is the same as the lubricant for bearings will be re-circulated. The coolant will take over the heat resulted further to the friction between the components in relative motion of the transmission and bearings and will dissipate it outside, so that the preloading force of the double nuts recommended by the ball screw manufacturer Gamfior [6], will remain constant, as shown through the equation (5):

\[
F_{pr} = \frac{F_A}{2.83}
\]  

(5)
On the other side, the same circuit of the coolant will contribute to control through thermostat the bearings of the ball screw; these bearings are closed into oil tight boxes inside which the coolant flows, thus paying its double role, i.e. to lubricate the radial-axial bearings and to keep a constant temperature into the bearings.

Figure 2 shows the bearing system at both ends of the ball screw with thermostatic control. This bearing system at both ends with thermostatic control has been applied on a CNC machine tool manufactured by the machine tool company W.M.W. Bacau.

![Figure 2. Thermostat of the ball screw bearing system.](image)

Where: 1- admission of the thermostat agent; 2-bearing body; 3-left side radial-axial bearing; 4-bearing box; 5-sealing ring; 6-ball screw; 7-right side radial-axial bearing; 8-mechanical clutch; 9-servomotor; 10-evacuation of the thermostat agent.

The coolant will enter the left bearing of the ball screw through the admission hole, afterwards it will flow through the inner bore of the ball screw; then it will reach the right side bearing of the ball screw and will be directed outside through the drainage hole along with the heat accumulated along the circuit.

4. Heat transfer from ball screw to outside

The heat transfer through convection from the ball screw to the outside is performed by the forced circulation of the coolant and lubricant oil through the inner bore of the ball screw, as schematically shown at figure 3.

![Figure 3. Schematic representation of the heat flow during the ball screw cooling.](image)

The transfer function of the heat from the ball screw to the outside is described by the equation (6):

$$
\Delta Q_g = q_q L_q \Delta \theta
$$

Where: $\Delta Q_g$-convection heat at the ball screw output; $q_q$-coefficient of thermal transfer; $L_q$- length of the ball screw; $\Delta \theta$-variation of the heat difference between ball screw and coolant. Since the oil that represents the coolant used for the ball screw thermostatic control is the same as the coolant and lubrication oil for bearings, it has to comply with several physical properties that are shown at table 1.
Table 1. Physical properties of the coolant.

| Property            | Value          |
|---------------------|----------------|
| Density $\rho$      | 882 (Kg/m³)    |
| Viscosity $\nu$     | 0.07 (Kg/ms)   |
| Thermal conductivity $\lambda$ | 0.130 (W/mK)  |
| Specific caloric capacity $c$ | 1.95 (KJ/KgK) |

As such, starting from the Reynolds criterion, when the angular speed of the ball screw is known and, based on the physical properties of the coolant shown at table 1, the equation (7) may be written. It represents the main parameter for performing a laminar flowing in the cooling circuit:

$$Re = \frac{\omega L_s}{\nu_f}$$  \hspace{1cm} (7)

Where: $\omega$-angular speed of the ball screw; $L_s$-length of the ball screw; $\nu_f$-coolant viscosity.

During the lightly turbulent flowing, when the coolant enters the bearings or the ball screw bore, the Nusselt invariant may be written as shown in the equation (8):

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$  \hspace{1cm} (8)

The coefficient of thermal convection will be determined by means of the equation (9):

$$C_c = \frac{Nu_d}{L_s}$$  \hspace{1cm} (9)

Thus, the thermal flow issued by the ball screw and its bearings will be settled through the equation (10):

$$F_t = C_c V(t_s - t_f)$$  \hspace{1cm} (10)

Where: $V$-volume of coolant; $t_s$-ball screw temperature; $t_f$-coolant temperature

In this case the convection heat transmitted from the ball screw to the outside will be given by the equation (11):

$$Q = F_t T$$  \hspace{1cm} (11)

Where: $T$-transfer time.

The transfer heat is different on the three axes X, Y, Z of the machine tool because the ball screws have different lengths and different angular speeds as well. Based on summing the convection heat on all kinematical axes of the machine tool, the input data for sizing the coolant unit will be settled.

5. Experimental results

The experiments have been carried out on all translation axes of a CNC machine tool that has the following travels on axes: $X=700$ mm, $Y=600$ mm and $Z=500$ mm, and the feed rates of the three axes are 40 m/min, being submitted to an average load of 3500 N, for a time interval of 180 minutes. The first set of trials has been done without thermostats on the ball screws and their bearings at an environmental temperature of 21°C, recommended for industrial environments. During the testing cycle the moving elements moved along their entire travels. The experimental results are presented in the diagram at figure 4.
Figure 4. Temperature curves in function of time, without thermostats on the axes.

Figure 5. Temperature curves in function of time, with thermostats on the axes.

It resulted that on all three axes the temperatures of the ball screws have increased from the initial value of 21°C to maximal values ranging from 43°C to 47°C in approximately 40-45 minutes after the start-up of the testing cycle. These maximal temperatures remain relatively constant during the time interval of 50-180 minutes. The second set of trials has been carried out under the same conditions but with controlled thermostatic of the axes. The related experimental results are illustrated through the diagram at figure 5. As it may be noticed at figure 5, when the ball screws and their bearings are cooled with thermostatic oil, their temperatures are substantially lowered and kept around the value of 21°C during the entire running time of 180 minutes. In this case the thermo-mechanical deformations of the mechanisms are minimal and the new positioning errors of the moving elements are low. The thermostatic system of the axes is efficient, especially in our case where the position measurement of the moving elements is performed indirectly, by means of rotary encoders located on intermediary elements of the feed kinematical linkages, just on the spindle of the driving servomotor. The indirect measurement system does not have the capacity to cover and compensate the positioning errors of the moving elements caused by thermo-mechanical deformations and, through thermostats, their negative influence is decreased.

6. Conclusions
The thermostatic control of the ball screw-nut subassembly and its bearings leads to a stability of the system that means a constant and uniform running of the machine tool during the entire production cycle. By keeping constant the temperature of the ball screw and its bearings, the modification of the preloading forces of the double nuts and of the bearings will be avoided, thus providing a constant efficiency of the ball screw mechanism. Another negative issue concerning the absence of the thermostatic control occurs when sudden accelerations and decelerations come up; this leads to very high friction forces and, by default, to the generation of a high temperature, with effect on decarbonising the contact surfaces. Through thermostatic control, this undesirable issue is removed.

As far as the lubricant of the ball screw, nut and bearings subassembly is concerned, this will be maintained at a constant viscosity that means that the lifetime of the lubrication will be longer. The thermostat systems of the ball screws and their bearings are decreasing the heat propagation to other neighbouring components that, on their turn, may affect the positioning accuracy of the machine tool. By means of the thermostatic control, the time of the machine heating can be considerably shortened and the machine tool will have the capacity to get in production after a much shorter time. Through thermostatic control at source, of the ball screw, nut and its bearings, the undesired effects of the thermo-mechanical dilatation that provoke stresses between the components of the kinematical linkage, are eliminated. In this manner a higher reliability of the ball screw - nut mechanism is
obtained, as well as running at high feed rates for an increased productivity. The most important aspect consists of obtaining a high positioning accuracy on all three axes of the CNC machine tool.

7. References
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