Thermal influence on the positioning accuracy of the CNC machine tool rotary tables

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Abstract: This work analyses the perturbing thermal sources and design solutions to avoiding the thermal effects. The analysis is focused, as main factors of the thermal dilatation, on the rotary tables, the guiding systems, the radial one and, especially, the axial one (that takes over the weight of both table and work piece), as well as on the positioning of the driving servomotor that is a thermal source in the vicinity of the rotary table. The new solutions presented in this work refer to the rotary tables with direct measuring whose number of indexing positions is 360000 that means a minimum increment of 0.0001 degrees. It is to be mentioned that this structure allows the kinematic linkage of the rotary table to take part to machining. If the rotary table provides positioning only, the table will have a clamping system that confers a high stiffness, needed for heavy duty cutting. The experimental trials have been carried out on a machining centre of the Micro-production workshop of the University in Bacau. The size of the rotary table is 630x630 mm. Repeated trials have been performed for determining the positioning accuracy through the modification of the thermal conditions of the worm-wormed gear mechanism. The results have proven an enhancement of the positioning accuracy of approximately 7%.

1. Introduction
The positioning accuracy of the rotary tables is a priority of the machine tool builders that aim at improving or even eliminating the positioning errors [1]. The positioning accuracy of the feed kinematic linkages to which the rotary tables belong [2], is influenced by a series of factors: constructive, thermal, stiffness. The thermal sources of influence [3] of the CNC machine tools consist of both internal and external sources [4]. Thermal influences are negatively affecting the machine accuracy. This issue has led to thinking of and designing new solutions, such as the isolation of the thermal sources of the machine tool structure, by using a more rigorous control of the temperature during the machine running.

2. Constructive analysis of the rotary tables of the CNC machine tools
The constructive structure of the rotary tables that, in most of the cases are integrated to the machine tool assembly depends on their role in the cutting process. Thus, in the first variant, if the rotary table is intended setting the work piece (like in the case of the milling and boring and milling machines) it will provide the position indexing at certain angles with a view to machine more surfaces of the work piece. The category of this first variant includes the rotary tables that perform precise positioning at 4x90°; 8x45°; 72x5° and 360x1°. The table indexing is performed at idle running that leads to an adequate sizing of the feed kinematic linkage that will be driving the table. The table indexing is
performed at certain time intervals and the duration of the positioning process is relatively short, within 0.2 – 2 minutes. At this type of rotary tables the positioning accuracy is usually assured by mechanical means, such as: bolt or prism type indexing, through frontal clutch with 72, 180 or 360 teeth. After performing each positioning process the table will be clamped, so that a good stiffness is provided, for the cutting process to be carried out under proper conditions. The positioning accuracies obtained by this constructive variant of rotary table, encountered at many machine tool manufacturers (Yasda, Mandelli, Csepel, Cincinnati etc.) range within ± 1 sec and ±3 sec. Out of the constructive description of above it results that in case of this type of rotary table the thermal sources are relatively low, because the indexing is performed periodically and its duration is short, i.e. 1 minute maximum. At the same time, the accuracy of the positioning is given by the mechanical indexer; as such, the thermal influences at this type of rotary tables are low, even neglected in cases when indexing is rarely performed. The second variant of rotary table that is more and more frequently used is that one that provides positioning at 360000 positions having a programmable minimum increment of 0.001 degrees. In other words, this rotary table is controlled in canned cycle, having the possibility to perform individual cutting or to take part to cutting, along with the other controlled axes of the machine, for performing plane or space interpolations. At the same time, the second variant of rotary table can also perform indexing at certain angles for machining more surfaces of the work piece. The positioning accuracies provided by this rotary table variant differ from builder to builder, having values within ±5 sec. and ±20 sec. It is to be noticed that feed kinematic linkage of this constructive variant is sized for running at load and the cutting time at load is not limited. From this point of view the influence of the thermal regime of the table is found on the positioning accuracy.

3. New constructive solution of rotary table with thermostatic worm – wormed gear mechanism

In order to improve the positioning accuracy a new structure of a rotary table has been conceived with positioning possibilities at 360000 positions. This concept of rotary table has a controlled axis and can take part to cutting through plane or space interpolation. This solution is suitable for small and middle size rotary tables, i.e. 320 x 320 mm, 400 x 400 mm, 500 x 500 mm, 630 x 630 mm, 800 x 800 mm and 1000 x 1000 mm. Figure 1 presents, in cross section, the new constructive solution. The moving element 1 that represents the table itself is solidly fixed to the central pivot 2 by means of bolts and the tapered surface on the top side; to the rotary table itself the wormed gear 3 is also fixed that gears with the worm 4. The rotary table has a radial bearing through the roller bearing 4 and axial (thrust) bearing through the thrust bearings 5. The thrust bearings are preloaded ad their position can be adjusted by means of the spacer 7 so that the contact with the surface 8 (the “mirror”) can be done, thus providing both a good stiffness and the possibility for clamping the moving element 1. This moving assembly presented above is supported, through the bearings, by the saddle 9 that, on its turn, moves horizontally along the guideways 10. The clamping system of the table 1 consists of six disk springs sets 11 equidistantly located and the unclamping is performed through the hydraulic cylinder 12 that has a supporting collar on its top side. The position encoder 13 is located at the inferior side; it has the cursor fixed to the pivot 2, thus providing the direct measurement of the motion of the moving element 1. The driving system is composed of a servomotor coupled to the wormed gear 4 by means of a clutch. The wormed gearing is duplex type, giving the possibility to adjust the backlash between the tooth flanks through the axial motion of the worm. The wormed gearing has been chosen as transmission system even though its efficiency is relatively low (0.74) for dimension and vicinity reasons, as the internal structure of the rotary table is complex. The positioning of the moving element 1 goes through the following steps: 1- The moving element moves at high rpm towards the programmed point; 2- before positioning a deceleration is performed and change to a low rpm (creeping); 3- stop when reaching the programmed point; 4- clamping of the moving element, at the same time with interrupting the position loop of the axis control. While clamping the axis that is performed against the surface 8, the oil film formed on the “mirror” is crashed if he moving element moves at rapid feed.
Figure 1. Rotary table – cross section.

Where: 1-moving element; 2-central pivot; 3-wormed gear; 4-worm; 5-roller bearings; 6-axial bearings; 7-spacer; 8-with the surface (the “mirror”); 9-saddle; 10-guideways; 11-pack of disk springs equidistantly located; 12-hydraulic cylinder; 13-position encoder.

Because of the light flatness deviations of the surface 8, during the oil film crashing components of the forces that require additionally the moving element 1 come up, leading to slight swings that affect the positioning accuracy. These influences may be seen on the numerical control readout, even though the controlled axis is clamped. Theoretically, the transmission system composed of the wormed gearing is irreversible but, because of the backlash between the tooth flanks the occurrence of this deviation is possible. Even though the backlash in the wormed gearing has been minimised during running, because of its modest efficiency a thermal source will come up that will modify the value of the backlash between the tooth flanks. In order to reduce the thermal influence on the new solution, the wormed gearing will be thermostatic.

Figure 2 shows a schematic presentation of the way of thermostating the duplex type wormed gearing of the rotary table. The installation is designed to keep an optimal running temperature, namely 20°C - 22°C, during the entire functioning time of the rotary table. The system of above uses a Freon unit from the machine endowment in order to refrigerate the cooling – lubrication liquid, bringing it to the optimal running temperature. The liquid is circulated through the unit 2 that is provided with cooler and pump. The pump takes the lubricant from the wormed gearing by means of tour and retour pipes. After cooling, the lubricant is resent to the wormed gearing. Another feature of this system consists of the fact that through the cooling of the lubricant, a relatively viscosity coefficient is maintained, giving a good lubrication. Inside the wormed shaft a drill has been done to facilitate the flowing of the cooled lubricant that enters through the left side. It has a double role, i.e. to lubricate the wormed gearing and to take over the heat generated by the friction forces in the rotary table gearing. Because the new solution of rotary table presented above is available for cutting, the resistant forces require such a sizing of the bearing system of the duplex wormed gearing, to assure a very good stiffness.
Figure 2. Schematic presentation of the duplex wormed gearing thermostat.

For this reason, on both ends of the wormed gearing needle bearings 4 are used, mounted into the boxes 5 that, on their turn, are provided with adjusting parts in order to allow the axial motion of the worm in order to eliminate the backlash between the tooth flanks. As it has been shown at figure 1, the inner lubrication of the rotary table is mist type lubrication and half of the worm diameter is immersed in oil. In this way, through the worm thermostatic, the cooling of the oil mist is provided as well. The friction and rolling forces between the parts, the friction forces into the bearings etc. lead to heating and wearing the wormed gearing, so it is an energy waste. If it is deemed that the entire lost energy is transformed into heat, the quantity of heat into which the lost energy is transformed, would be:

$$Q = \frac{P(1-\tau)}{427}$$

(1)

Where: $P$ is the power transmitted to the nearing; $\tau$ -efficiency.

The relation of the heat quantity may also be written under the following form:

$$Q = 632 (1 - \tau) P \left[ \frac{\text{cal}}{h} \right]$$

(2)

At the same time, the heat quantity conveyed to the environment is:

$$Q = k(t_1 - t_2)S = k\Delta t S$$

(3)

Where: $k$- is the thermal conductivity; $t1$- oil temperature; $t2$ –ambient temperature which is 20°C; $S$- surface of the housing that is washed inside by the lubricant and outside is exposed to air circulation. The establishing of the thermal balance gives the relation:

$$632(1 - \tau)P = k\Delta t S$$

(4)

The temperature increase $\Delta t$ in the gearing is:
\[ \Delta t = \frac{632(1 - \epsilon) P}{kS} \]  \hspace{1cm} (5)

Based on the relations of above the thermostatic source needed for cooling the rotary table can be determined.

4. Experimental trials
The new solution of rotary table has been applied on a machining centre (milling) having the rotary table size of 630 x 630 mm. The machining centre is fitted with the Freon unit for the main spindle thermostat and the ball screw bearings on the three axes X, Y and Z. Trials consisted of determining the positioning accuracy of the rotary table (B axis) in two situations: without the worm gearing thermostat and with worm gearing thermostat. The positioning accuracy has been measured by means of a laser interferometer and a polygonal prism with 24 mirrors. The diagrams of the positioning error p in function of the angle \( \alpha \) of the rotary table are shown at figure 3.

Figure 3. Diagrams of the positioning accuracy.

Where: \( X \) – without thermostat; \( O \) – with thermostat.

The analysis of the two diagrams shows an improvement of the positioning accuracy by 7% in the case of using the thermostat on the duplex wormed gearing. This aspect is due to the fact that the backlash in the wormed gearing has been initially taken over, whilst in the thermostat variant it has been kept constant; consequently, upon the table clamping (after positioning) the wormed gearing keeps fixed the table position.

5. Conclusions
The new solution of rotary table presented in this work provides an improvement of the positioning accuracy and is recommended in cases when the machine tool is fitted with a thermostat source. Even though the increase by 7% only of the positioning accuracy in relation to the effort of implementing this solution is not very spectacular, the improvement is however obvious. In case of the CNC machine tools of small to middle size the solution being presented offers the machine tool designers and builders an accessible variant to improve the positioning accuracy.

6. References
[1] Suzuki T 2019 Improved method for synchronizing motion accuracy of linear and rotary axes under constant feed speed vector at end milling point Int. J. Automation Technol. 13 679-690.
[2] Jingxia Y 1998 The real-time error compensation technique for CNC machining systems Mechatronics 8 359-380.
[3] Lee H 2002 Statistical optimization and assessment of a thermal error model for CNC machine Tools The International Journal of Machine Tools and Manufacture 42 147-155.
[4] Ryuta S 2007 High performance motion control of rotary table for 5-axis machining centers Int. J. Automation Technol. 1 113-119.