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Measuring, modeling and compensating thermally caused location errors of rotary axes

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Abstract
This paper presents the results of a detailed thermal analysis of the Mori Seiki NMV 5000 DCG machine tool at IWF / ETH in Zurich with focus on the rotary axes. The rotary axes are characterized in detail regarding their position and orientation errors as a function of the underlying thermal load, contributing significantly to the overall accuracy of the 5 axis machine tool. A physical model is presented, which allows the simulation of the thermal behavior of the rotary axes based on the power input to the drives of the rotary axes and the heat conduction in a swivelling rotary table unit and into environment. This enables an external online-compensation of thermal errors and is verified and validated.

Keywords: Thermal behavior, 5-Axis machining, Modeling, Simulation

1 INTRODUCTION
Thermo-mechanical deformations caused by different internal or external heat sources are responsible for up to three quarters of all geometric errors of machine tools, which shows the big potential of thermal compensation regarding higher accuracy of machine tools [1], [2]. Until now, most of the research work has been concentrated on thermo-mechanical deviations based on the influence of moving linear axes, rotating spindles and on temperature variation of the environment [3]. According to this, a lot of measurements were done and guidelines how to handle corresponding deformations were developed with ISO 230-3 and ISO 10791-10 [4], [5]. Besides detailed measurements and the thermal characterization of different contributors (like the environment [6], spindles [7] or linear axes [8]), several compensation possibilities and strategies were developed and enhanced. This ranges from the simulation and compensation of single components like spindles in [9] to integrated compensation models for whole machine tools in [10]. Even though standards [11] exist for measuring the geometric errors of rotary axes, little research has been made on the thermal errors of rotary axes (except spindles), which is the focus of this paper. First approaches for the characterization of rotary axes are presented in [12], [13] and [14]. First results regarding the magnitude of the thermal errors of rotary axes show the importance of these influences.

External influences like the environment and power losses, that cause a heat transfer and change of temperature distribution in the machine tool, are the root causes for thermal deviations. The result is mechanical deformation and finally an error of the position of the tool center point (TCP) which can be decreased by two approaches. On the one hand, causes can be minimized. This can be carried out by several tasks: for example by the reduction of friction, by tempering of certain machine parts, by an intelligent utilization of different materials or in general by a more thermo-symmetrical design of the entire machine tool. On the other hand, a decrease of the TCP error can be reached by an NC-based reduction of the deviation, which means the compensation of the thermal error. In this paper, a compensation model for thermally induced position and orientation errors of rotary axes is presented. This model is based on five discrete elements which describe the analyzed machine tool with its swivelling rotary table unit. The discretization is based on knowledge of thermal behavior of rotary axes of the machine tool under investigation. Due to its simplicity it enables an online-compensation of thermal effects which is validated by measurements.

2 CHARACTERISATION OF AXES OF ROTATION
To be able to compare the thermal influence of the rotary axes to the influence of other sources like the environment, the spindle or the linear axes, comprehensive measurements were carried out according to ISO 230-3. After that, measurements regarding the behavior of the axes of rotation were carried out [12]. Results have shown errors in the same range as from other contributors, which was the reason for a detailed analysis.

Figure 1: Investigated machine tool NMV5000DCG with axes and coordinate system, adapted from [13]

Figure 1 shows the analyzed machine tool Mori Seiki NMV 5000 DCG with its axes and the machine tool coordinate system.

Position / Orientation errors of interest
In [14], 5 position and orientation errors (hereinafter “location errors”) are defined for a rotary axis C. These are
the position errors X0C, Y0C in X- and in Y-direction, the squareness B0C, A0C to X and Y and the zero angle deviation C0C of C.

In addition to these deviations, other location errors of functional surfaces exist, which are not defined in the standard, because [11] covers geometric errors only, and because [4] currently does not cover rotary axes. Two significant examples are shown in Figure 2: The axial and radial growth ZOT and ROT of a machine table with changing temperature.

The measurement sequence for the determination of thermo-mechanical errors of rotary axes is subdivided into a warm-up phase and a cool-down phase of each 4 hours. Every 5 minutes, a R-test measurement with a duration of approximately 60 s is carried out. Every phase consists of axis movement cycles (about 5 minutes) and probing cycles (< 1 minute). The total net warm-up time is at least 4 hours, which means that there are at least 48 axis movement cycles per warm-up phase. The same measurement sequence applies for the cool-down phase (with no axis movement). With a probing cycle time of < 1 minute, the total test duration is about 9.5 hours. In this paper, all measured deviations are illustrated over the net warm-up / cool-down phase of 8 hours – measuring time is cut out. For all long term measurements, the environmental temperatures are registered continuously.

Measuring sequence

The measurement sequence for the determination of thermo-mechanical errors of rotary axes is subdivided into a warm-up phase and a cool-down phase of each 4 hours. Every 5 minutes, a R-test measurement with a duration of approximately 60 s is carried out. Every phase consists of axis movement cycles (about 5 minutes) and probing cycles (< 1 minute). The total net warm-up time is at least 4 hours, which means that there are at least 48 axis movement cycles per warm-up phase. The same measurement sequence applies for the cool-down phase (with no axis movement). With a probing cycle time of < 1 minute, the total test duration is about 9.5 hours. In this paper, all measured deviations are illustrated over the net warm-up / cool-down phase of 8 hours – measuring time is cut out. For all long term measurements, the environmental temperatures are registered continuously.

Measuring device: R-Test discrete

A measuring device for the characterization of thermo-mechanical errors of rotary axes should show the following properties:

- Acquisition of all significant errors within one measurement cycle
- Short measuring time to avoid significant changes of the thermal state during the measurement
- High accuracy
- High repeatability

Different investigations in [12] [16] [17] regarding this topic show that the R-Test according to [15] has figured out as a proper measuring device for this application. For this paper, measurements are carried out as “R-test discrete” according to Figure 3. Each probing cycle consists of five single measurements at 0°, 90°, 180°, 270° and 360° of the axis under test. The probing cycle time is kept smaller than 1 minute in order to avoid thermally caused deviations of the machine tool during the measurement cycle.

The five measuring positions enable the evaluation of all significant location errors of rotary axes plus errors of functional surfaces like axial or radial growth of the table, ZOT or ROT. With this procedure, the B- and C-axis of the NMV5000DCG were analyzed for different rotational speeds and therefore for different input power levels. The coordinate system of all illustrations is chosen in that way, that deviations in all diagrams show the relative work piece shift (in the work piece coordinate system, not in the machine coordinate system).

Selected examples for thermal deviations

As an example for the resulting location errors, Figure 4 shows Y0C, the location error of the C-Axis in Y-direction, caused by heat generated by the C-Axis direct drive for rotational speeds between 200 and 1200 min⁻¹.

The maximum deviation of 25 μm appears at the rotational speed of 1200 min⁻¹. Two interesting effects can be seen in Figure 4: 1.) the errors don’t reach the zero level again after the cool down phase. This can be explained by the change of the environmental temperature during the measurement. 2.) The course of the error shows a combination of two lag elements. This can be explained, because heat input is
non-homogeneous around the C-axis drive. Comparable to the bi-metal effect, this leads to an angular error. After a certain time, heat conduction in the structure leads to a homogenizing of the temperature contribution in the swivelling rotary table unit. Therefore, the thermally induced error (like Y0C in Figure 4) is decreasing again after a while.

The tests shown in Figure 4 were carried out over a period of approximately 3 weeks. The environmental temperature was not constant during this time. Also each single test is underlying a temperature variation which is carefully registered for further consideration.

Figure 5 shows the squareness A0C of the C-Axis to the Y-Axis in μm/m. The magnitude of the deviation is -12 μm/m after approximately 1 h with a rotational speed of 1200 min⁻¹. According to Y0C (Figure 4), A0C is decreasing after approximately 1 h at all rotational speeds except 800 min⁻¹.

![Figure 5: Squareness of C-Axis to Y-Axis (A0C) for 6 different rotational speeds](image)

After analysis of the swivelling rotary table unit, the four location errors Y0C, A0C, R0T and Z0T were detected as significant errors. Errors in X-direction and B-direction are not significant due the design of the machine tool which leads to a symmetric temperature field with respect to the Y-Z-plane. The four significant errors should be minimized and compensation seems to be a promising procedure.

3 MODELING AND SIMULATION OF THERMAL EFFECTS

There are many different approaches for simulating the thermal behavior of machine tools like FEM models, phenomenological models or simplified physical models using transient heat conduction. The outstanding characteristic of a simplified, physical model is the small modeling and computing effort which also allows the implementation of the compensation model in an NC. A possible alignment of model and measurements can improve the simulation (e.g. density, heat transfer coefficient, effective boundaries,...) and the physical background enables a simulation and prediction of conditions, not covered by experiments. Therefore this paper describes an approach for modeling the thermally induced location errors of the rotary axes by a simplified physical model.

Model structure

For the simulation a thermobalance model is set up, here the significant part of the machine tool was discretized in 5 parts according to Figure 6. The background for this segmentation is based on measurements which are carried out characterizing the C- and the B-axis. The 4 errors Y0C, Z0T, R0T and A0C which are evaluated as the significant deviations can be simulated with the described configuration. Because of the thermo-symmetrical design of the machine tool with respect to the Y-Z-plane a 3D model is not necessary.

![Figure 6: Simulation model with discretized swiveling rotary table unit](image)

The discretized bodies are chosen such, that temperature can be assumed as homogenously distributed in every body. Depending on the temperature changes, the associated thermo-mechanical deformation and therefore the deviation of the TCP is calculated. Input parameters for the calculation are the geometry data for all bodies with i = 1…6, power input (P₁), cooling power (P₂), mass (mᵢ), thermal conductivity (λᵢ), heat transfer coefficients for convective flow (αᵢ) and specific heat capacities (cᵢ).

The basic principle for the calculation of the single temperatures is found in the law of energy conversion:

\[
m \cdot c_p \cdot \frac{dT}{dt} = \sum \dot{Q}
\]

(4-1)

where m is the mass, cₚ the specific heat capacity, T the temperature and Q the heat flow. Based on this relationship, the temperature of the 5 discretized bodies is calculated every 0.5 seconds with

\[
T(t_{i+1}) = T(t_i) + \frac{\sum \dot{Q} \cdot \Delta t}{m \cdot c_p}
\]

(4-2)

While geometry data, mass, heat transfer coefficients and heat capacity are known or can be estimated very well, the power input of the drives is read out of the FANUC NC in real time for online-compensation.
The cooling power $P_c$ is calculated via:

$$P_c = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \quad (4-3)$$

$V$ is the Volume flow rate and $\rho$ is the density. As the volume flow rate is not known, cooling power is estimated based on information from the supplier of the cooling unit.

Heat conduction between the single discretized bodies $k$ and $j$ is calculated from

$$\dot{Q}_{c,k,j} = \frac{\lambda}{l} \cdot A \cdot (T_j - T_i) \quad (4-4)$$

$\lambda$ is the heat transfer coefficient, $A$ is the cross-section area, $l$ is the effective length and $T_i$ is the Temperature of the body $i$.

Finally, with the environmental temperature $T_u$ known as starting condition, convection is calculated from:

$$\dot{Q}_{\text{conv}} = \alpha \cdot A \cdot (T_u - T) \quad (4-5)$$

Therefore, the heat transfer coefficients for convective flow $\alpha$ has to be determined. During standstill, $\alpha$ is estimated for the underlying geometry with

$$\alpha = 3.2 \frac{W}{m^2 \cdot K} \quad (4-6)$$

In [18] and [19], heat transfer measurements of a rotating disk were carried out. According to these investigations, the heat transfer coefficients for convective flow $\alpha$ is calculated for different rotational speeds. For the maximum rotational speed of 1200 min$^{-1}$, equation (4-7) delivers a convection coefficient of

$$a(1200 \text{min}^{-1}) = 65.5 \frac{W}{m^2 \cdot K} \quad (4-7)$$

which is approximately factor 20 higher than the convection coefficient during standstill.

With all the parameters described above, the temperature of each of the discretized bodies is calculated according to (4-2). In order to verify these calculations, temperature measurements are carried out.

Figure 7: Air temperature in working area and comparison between measurement and simulation of table temperature ($n=600 \text{ min}^{-1}$)

To enable dedicated measurements on the rotating table, a wireless temperature measurement device is developed: a National Instruments cDAQ-9191 measurement system is used with a National Instruments TB-9214 WIFI module, powered by a Lithium-Polymer battery pack. This enables online temperature measurements of the rotating machine tool table.

Figure 7 shows the comparison between the measurement (blue curve) and the simulation (red curve) of the table temperature. The measurement is the mean value out of 3 measurement positions. The underlying thermal load is an axis rotation with 600 min$^{-1}$ for 4 hours, followed by a 4 hour cool-down phase.

During warm-up phase, both - simulation and measurement – are matching very well. Also during cool-down phase, the simulation result is quite good, but there are two effects to notice: First, at the start of the cool-down phase there is a short temperature peak in the measurement plot, which can be explained by a strong decrease of convection due to the stop of the rotation in combination with a proceeding thermal flow from the drive to the surface of the table for a short time.

A second interesting point can be seen at ~6.5 h: after the temperature is decreasing, it rises again with another delay time. The explanation for this effect is, that the cooling unit stops cooling the swivelling rotary table unit which leads to a convergence of the table temperature to the environmental temperature (black curve).

On the one hand, Figure 7 shows the good quality of the simulated temperatures – on the other hand, especially concerning the cool-down phase, two possibilities for an improvement of the simulation could be identified.

Based on the temperature changes of the single bodies, the geometric deformations are calculated according to:

$$\Delta l = l_0 \cdot \alpha_e \cdot \Delta T \quad (4-10)$$

$\alpha_e$ is the thermal expansion coefficient.

4 COMPENSATION OF THERMALLY CAUSED LOCATION ERRORS

With the dimensional changes known, the 4 significant location errors $Y_0C$, $Z_0T$, $R_0T$ and $A_0C$ are calculated in real time and used for the computation of compensation parameters for each axis, which then are sent to the CNC online every 0.5 s. The notation which is used for the description of the single compensation parameters is illustrated in Figure 8.

Figure 8: Notation of considered compensation parameters

The compensation parameter for the Y axis due to $Y_0C$ is

$$C_{Y,Y_0C} = -Y_0C \quad (5-1)$$

and has only one component because of its independence of the swiveling angle of the B-axis.
Regarding the compensation of \( Z0T \)

\[
C_{X,Z0T} = -Z0T \cdot \sin \hat{B} \\
C_{Z,Z0T} = -Z0T \cdot \cos \hat{B}
\]  

\( (5-2) \)

are the parameters to compensate the X and Z axis respectively depending on the angle of the B-axis. \( \hat{B} \) represents the angle of the B-axis. The symbol \( \hat{\cdot} \) identifies parameters, which are read out of the NC on-line.

The compensation of the radial table growth \( R0T \) is computed according to

\[
C_{X,R0T} = -\hat{X} \cdot \frac{R0T}{r} \cdot \cos \hat{B} \\
C_{Y,R0T} = -\hat{Y} \cdot \frac{R0T}{r} \\
C_{Z,R0T} = -\hat{X} \cdot \frac{R0T}{r} \cdot \sin \hat{B}
\]  

\( (5-3) \)

Because the radial table growth increases with an increasing offset to the C-Axis (radius \( r \)), \( R0T \) is related to this radius \( r \) (location where the precision sphere is mounted during the R-tests measurements). Because of this position dependency the relative spindle position in the machine tool has to be read-out from the CNC on-line for computing the compensation parameters. With a tilting angle \( B \neq 0 \), the X-component of the compensation parameter in the table coordinate system is decomposed to X- and Z-component in the machine coordinate system.

Of course, \( (5-3) \) applies only for a constant height of the TCP above the machine tool table.

Finally, the rotary deviation \( A0C \) has to be compensated. For this, the machine tool has to offer an A-axis. The swiveling rotary table unit of the machine tool under investigation has a B-axis and a C-axis, but no A-axis. Therefore, an entire compensation of the squareness of the C-Axis to Y (\( A0C \)) is not possible, but the linear effects of \( A0C \) can be compensated.

Similarly to the radial growth of the table \( R0T \), this parameter strongly depends on the relative spindle position in Y-direction. Therefore, the Y-position of the spindle is read out of the CNC in real-time and is used for computing the compensation parameters in the machine tool according to:

\[
C_{X,A0C} = -\hat{Y} \cdot A0C \cdot \sin \hat{B} \\
C_{Z,A0C} = -\hat{Y} \cdot A0C \cdot \cos \hat{B}
\]  

\( (5-4) \)

For verification of the compensation, the thermal behavior of the machine tool is analyzed for an arbitrarily chosen thermal load profile as shown in Figure 9.

During this every 5 minutes an R-Test is carried out with a duration of <1 min. This leads to a total test time of approximately 8.5 hours. During the R-Test measurements which are evaluated for this paper, the offset of the precision sphere to the rotary axis \( C \) is 162.546 mm.

Figure 10 illustrates the improvement of \( Y0C \). In three areas (0 – 0.5 h, 3.5 – 4-5 h, 6.5 – 7h) a slight overcompensation can be seen. Anyway, the error is reduced significantly over the whole test duration.

![Figure 10: Improvement for compensation of \( Y0C \)](image)

Figure 11 shows achieved results compensating \( Z0T \). Finally, Figure 12 shows the reduction of linear effects of the squareness \( A0C \) of the C-Axis to Y. Especially in the first half of the cycle, the deviation is minimized significantly.

![Figure 11: Improvement for compensation of \( Z0T \)](image)

![Figure 12: Improvement for compensation of the linear effect of \( A0C \)](image)
The total reduction of the single location errors over the whole test cycle is summarized in Table 1. The improvement is calculated as reduction of the root mean squares of the deviations throughout the cycle, referenced to the starting point.

Table 1: Total improvement of compensation ($A0C_{lin}$ means the linear effect of $A0C$)

<table>
<thead>
<tr>
<th>Improvement [%]</th>
<th>$Y0C$</th>
<th>$Z0T$</th>
<th>$R0T$</th>
<th>$A0C_{lin}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>See Figure</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>27</td>
</tr>
</tbody>
</table>

All translational location errors are reduced by more than 70%, and even the – quite small – linear effect of the rotational error $A0C$ was reduced by one third.

5 CONCLUSIONS

To establish appropriate frameworks for a profound thermal characterization of the rotary axes NMV 5000 DCG machine tool, all other significant thermal influences like environment, linear axes and spindle are qualified. These measurements show that the magnitudes of the thermally induced location errors of rotary axes are in the same range as those from the other contributors. A simplified physical model is designed to simulate the significant location errors. As input parameters for the model, the power input for the C- and B-axis are used instead of the power loss, which might be different, but here is nearly not, because no chipping takes place. The model enables the allocation of compensation parameters in real-time. With a changed load cycle, the successful compensation of significant deviations is verified. Location errors can be reduced by up to 78%, and in the average over an arbitrary cycle by over 70%. The presented compensation procedure provides a very effective tool for reducing thermo-mechanical errors induced by rotary axes of 5-axis machine tools.

6 FURTHER STEPS

As mentioned before, a very important influence factor on the accuracy of compensation is the cooling power, provided by the cooling unit of the swivelling rotary table unit. Figure 18 shows the analogy between the computed and measured temperature values for a certain rotary speed (600 min$^{-1}$). An improvement of the simulation of the cool-down phase is needed. Therefore, measurements concerning the behavior of the cooling system are planned. In the current model, environmental temperature is only concerned for the starting conditions of the calculation. In the future, an ambient air temperature sensor will be implemented to permanently include the environmental temperature variation.

All work presented in this paper was carried out under dry conditions and without chipping, which means no cooling lubricant was used during measurements, no heat distribution by heated chips and the total electric power is lost nearly at the location of the drive motors. In the future, measurements with cooling lubricant are planned for characterizing the influence of coolant during machining on the location errors.

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REFERENCES

[13] PROGRAMMING MANUAL NMV 5000 DCG, Mori Seiki, the machine tool factory, 2009.