Compensation of cutting fluid influences on five axis machine tools

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Abstract

Thermally induced errors on machine tools are one of the most important error sources in precision machining. Up to 75 % of the overall geometrical errors on workpieces are caused by thermal errors of the machine tool [1]. This paper presents research carried out on Mori Seiki NMV 5000 DCG machine tool at IWF Zurich with a focus on the differences in thermal behavior of machine tools for dry or wet cutting on the machine rotary/swiveling axes unit. It is shown, that the thermal errors are enlarged on the machine tool under investigation with the use of cutting fluid. To compensate the occurring thermal errors a thermobalance and a phenomenological model are developed. Both compensation models show a promising approach to reduce the arising thermal errors of up to 90% under the influence of cutting fluid.

Keywords: Thermal error reduction, cutting fluid, five axis machine tool

1 INTRODUCTION

Modern precision manufacturing processes are strongly connected to the accuracy of machine tools. Basically three axis machine tools are used for manufacturing of high precision parts with geometrically defined cutting edges, like milling. Nevertheless, there is a demand for high precision five axis machined workpieces. Examples are found in the medical engineering and aerospace industries.

Thermal influences on machine tools are one of the most prominent source of errors on machined workpieces. Up to 75 % of the geometrical errors can be termed as thermally induced [1]. Bryan summarized the influences to the machined workpiece in the “thermal effects diagram” [2]. Sources that can cause thermal errors are:

- Room environment,
- Thermal memory from previous environment,
- People,
- Cutting process,
- Machine, and
- Coolants.

In Figure 1 a subdivision of the causes in external and internal influences is shown and the chain of effects that result in thermal errors at the tool center point (TCP) is illustrated as well as the possibilities for thermal error reduction on machine tools.

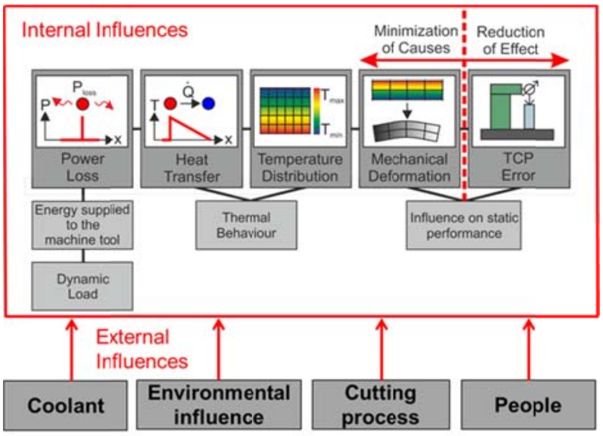

Figure 1: Chain of causes and thermal TCP-errors [3].

Neglecting the influence of the process and the people, for a long time research focused on regarding thermal TCP errors influenced by environmental temperature change, running the main spindle, and moving the linear axes. International standards developed regarding thermal errors on machine tools are ISO 230-3 [4], ISO 10791-10 [5], and ISO 13041-8 [6]. The procedures described in the standards are used for measuring the thermal error under no load or finishing conditions. Missing links in these standards are measurement procedures for additional thermal errors caused by rotary and swiveling axes of five axis machine tools [7,8]. Furthermore not considered in the standards are influences of cutting fluids on the accuracy of machine tools.

Several models for computing thermal errors have been developed in the past [1]. These models are usually used to reduce the thermal errors with the help of compensational movements when running the machine tools. Phenomenological compensation models can be adapted to any machine tool independent of its axis configuration and geometry. Gebhardt et al. [9] used a gray box model to compensate thermal errors of rotational axes of five axis machine tools consisting of a system of differential equations. IWF further developed a thermobalance model of the rotary/swiveling axes of a machine tool that consists of five thermally uniform bodies. Physical models such as thermobalance models require a deeper understanding of the machine tool structure and geometrical configuration than phenomenological models [9].

This paper presents an investigation procedure of the influences of cutting fluid on five axis machine tools. Further two of the above mentioned models development for compensating thermal machine tool errors are enlarged by the effects of cutting fluid. In section 2, the influence of cutting fluid on the precision of a five axis machine tool is shown. For full compensation of thermal errors of ratary/swiveling axis unit, using a thermobalance model, the model is extended by the influence of cutting fluid and introduced in section 3. In section 4, a phenomenological model is likewise extended by the influence of cutting fluid and used to compensate thermal errors on five axis machine tools. The paper ends with a conclusion in section 5 and an outlook on future research activities planned on the Mori Seiki NMV 5000 DCG in chapter 6.

2 CUTTING FLUID INFLUENCES ON MACHINE TOOLS

In previous research work performed on a Mori Seiki NMV 5000 DCG IWF shows that cutting fluid has a significant impact on the thermal behavior of the rotary/swiveling axis unit of five axis machine tools [10].

Measurements are performed while rotary axis of Mori Seiki NMV 5000 DCG is running with a speed of 600 rpm for at least four hours, with and without cutting fluid supply. During the measurement cycle infrared (IR) images are taken to investigate the difference in the temperature field of the rotary/swiveling axis unit.

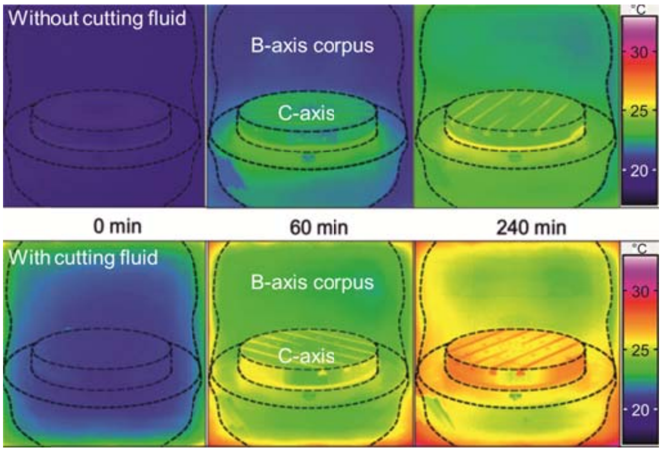

Figure 2: Thermography measurements of the rotary and swiveling axis with C-axis speed S = 600 rpm; left: measuring time t = 0 min; center: t = 60 min; right: t = 240 min; top: without cutting lubricant; bottom: with cutting lubricant; the temperature scale on the far right is given for uncorrected emissivity coefficients [10]

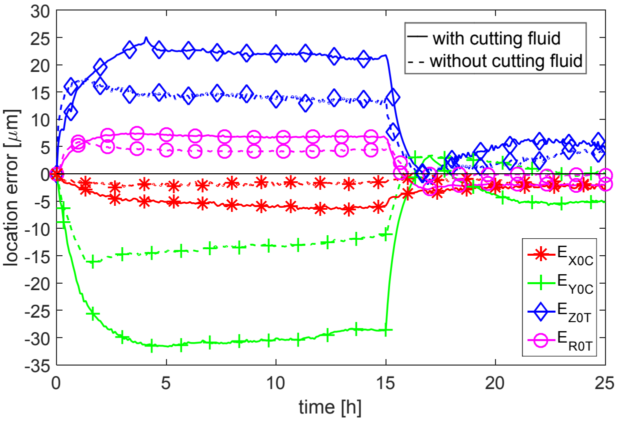

Figure 3: Translational errors measured with R-Test during a C-axis operation of 15 h warm-up at 600 rpm and 10 h cool-down phase at standstill; dashed lines: without cutting fluid, solid lines: with cutting fluid [11]

In Figure 2 the IR measurement results are shown for measurement times t = 0 min, t = 60 min, and t = 240 min with and without cutting fluid. The thermography images show three important differences:

- The temperature of the C-axis and the B-axis corpus is influenced by internal heat produced, when running the C-axis. Around the gap between the B-axis corpus and the C-axis both machine components are heated up. With the cutting fluid, a larger area around the gap is influenced.
- The C-axis becomes warmer, when cutting fluid is spread over the structure.
- The temperature of the B-axis corpus is influenced by the cutting fluid and also becomes warmer.

The measured temperatures are higher when cutting fluid is supplied than without use of cutting fluid. In consequence, also the measured thermally induced errors increase as illustrated in figure 3. During the warm-up phase the time to reach stead-state is enlarged on the machine tool under cutting fluid influences.

3 COMPENSATION OF CUTTING FLUID INFLUENCES USING A THERMOBALANCE MODEL

In [9,12] a thermobalance model for the compensation of thermaly induced errors of rotary and swiveling axes is presented. According to figure 4 the thermobalance model of the Mori Seiki NMV 5000 DCG is discretized in 5 bodies, so that the mean temperature of each body can be predicted. The deviation of the TCP is calculated by the thermo-mechanical deformation according to the associated temperature changes. The discretization of the model is based on measurements which are carried out characterizing the C- and the B-axis thermal errors. The four significant thermal errors E_{Y0C}, E_{Z0T}, E_{R0T} and E_{A0C} can be simulated with the described configuration. Due to the thermo-symmetrical design of the B-C-axes unit of the machine tool with respect to the Y-Z-plane, a discretization in X-direction is not necessary. The model considers three input factors for computing the thermal behavior of the machine tool: the environmental temperature, the power consumption of the drives and the internal cooling of the rotary/swivelling axis unit. As the model is small it is capable to compute the thermal errors online.

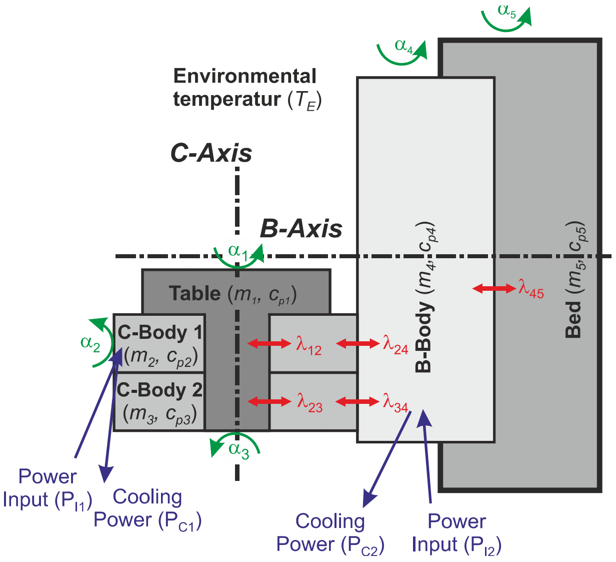

Figure 4: Simulation model with discretized rotary/swiveling table unit [12]

To extend the developed thermobalance model by cutting fluid influences, the convective boundary conditions and surrounding temperatures are modified. The areas which are connected to the cutting fluid are modified by the changed conditions. The areas to be modified are the surfaces of the body “Table” and “C-Body 1” in Figure 4, as these areas are flooded by the cutting fluid. To compute the convective boundary conditions of the rotary table surface a model from literature [13] is used. The configuration of the model is shown in Figure 5.

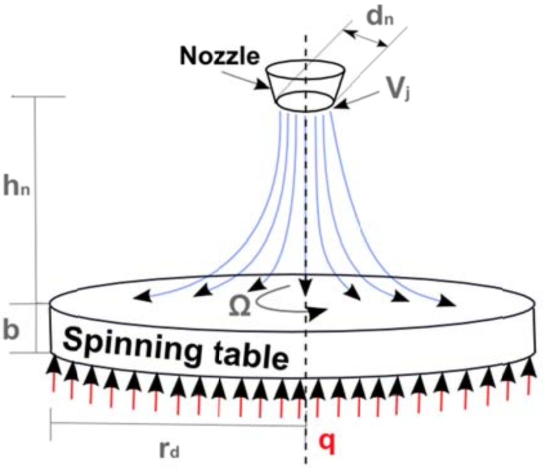

Figure 5: Model for computing convective boundary conditions of rotating table [13]

In Figure 5 d_n is the nozzle diameter, V_j is the fluid velocity, Ω is the rotational speed, r_d is the table radius, b is the table height, h_n is the horizontal distance of the nozzle to the upper table surface and q is the heat flow. The convective boundary conditions of the table surface are derived in [13] from computational fluid dynamics (CFD). As shown in Figure 5, the table is heated from below, which is the configuration in the machine tool. If the table is rotating, heat from the table bearings and direct drive motor is induced into the table.

The authors of [13] studied the influence of Prandtl number, Ekman number, Reynolds number, thermal conductivity ratio, and nozzle to table distance and correlated the Nusselt number on the table surface by:

$$Nu = 1.97619 \cdot \beta^{0.0909} \cdot Re^{0.75} \cdot Ek^{-0.1111} \cdot \varepsilon^{-0.9} \qquad (1)$$

In equation (1) Ek is the Ekman number, ε and β stand for:

$$Ek = \frac{v_f}{4 \cdot \Omega \cdot r_d^2} \qquad (2)$$

$$\varepsilon = \frac{\lambda_s}{\lambda_f} \qquad (3)$$

$$\beta = \frac{h_n}{d_n} \qquad (4)$$

In equation (2) to (4) v_f is the dynamic viscosity of the fluid, λ_s is the thermal conductivity of the table material and λ_f is the thermal conductivity of the fluid. The convective heat transfer coefficient h is computed by:

$$h = \frac{Nu \cdot \lambda_f}{d_n} \qquad (5)$$

The model is valid for:

- Ekman number: $4.42 \cdot 10^{-5} \leq Ek \leq \infty$
- Reynolds number: $500 \leq Re \leq 1500$
- Prandtl number: $1.29 \leq Pr \leq 124.44$
- Biot number: $3.73 \cdot 10^{-3} \leq Bi \leq 0.118$
- Rotational speed: $0 \leq \Omega \leq 750\,rpm$

The maximum rotational speed of the rotary table of the Mori Seiki NMV 5000 DCG is 1200 rpm. As the model is not valid for rotational speeds up to 1200 rpm, based on measurements on Mori Seiki NMV 5000 DCG, equation (1) is modified for higher rotational speeds up to 1200 rpm by replacing Ω by Ω_{new} in equation (2) by:

$$\Omega_{new} = \begin{cases} \Omega_{NC} & 0 \leq \Omega \leq 750\,rpm \\ 4 \cdot (\Omega_{NC} - 750)^5 + 750 & 750 < \Omega \leq 1200\,rpm \end{cases} \qquad (6)$$

In equation (6) Ω_{NC} is the rotational speed of the table read out from the numerical control (NC) of the machine tool. For parameter estimation and validation of the model under the influence of cutting fluid two different randomly generated test cycles are used.

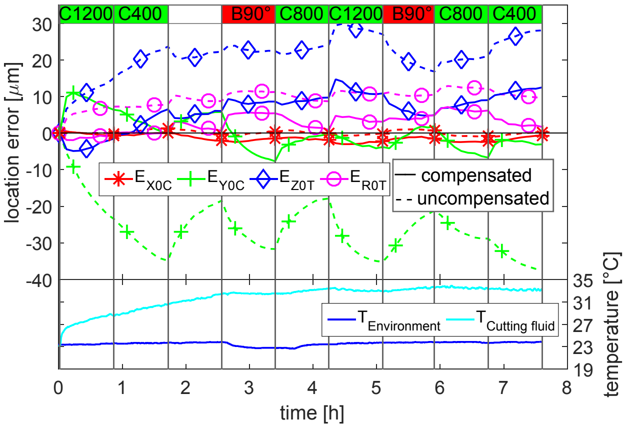

Figure 6: Measured thermal location errors E_{X0C}, E_{Y0C}, E_{Z0T} and E_{R0T} on machine tool with active compensation for nozzle height 50 mm, not compensated E_{X0C}

A fitting test cycle is used to estimate the model parameters which are used for all further compensation measurements and a validation test cycle is used to demonstrate the model’s performance and to avoid over compensation. The error E_{X0C} is small compared to the other thermal location errors and in the range of the controllable axis resolution of 1 μm. E_{X0C} can therefore not be compensated on this machine tool. As shown in figure 6, the model is capable of reducing the relevant thermal location errors of the machine tool under the influence of cutting fluid.

Figure 7 shows that the results with the validation test cycle confirms the results of the fitting test cycle. In both tests the nozzle height is 50 mm above table upper surface. Tests carried out with 100 mm nozzle height showed, that the model is capable of adapting to these changed conditions, based on the fact that the nozzle height is an input variable of equation (4).

In table 1 the relative reduction of thermal errors when compensating the machine tool under the influence of cutting fluid with a thermobalance model for both test cycles given. R-Test discrete measurements are evaluated for the quality criterion arithmetic mean. It can be seen that up to 90 % of the relevant thermal location errors can be compensated on the machine tool. Both test cycles show equal results when evaluating the improvement of thermal error compensation. Some of the errors show that with the second test cycle the improvement is slightly larger than with the first test cycle, which was used for parameter identification.

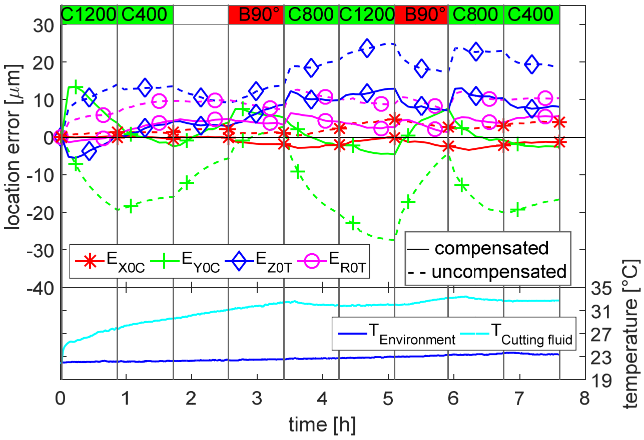

Figure 7: Measured thermal location errors E_{X0C}, E_{Y0C}, E_{Z0T} and E_{R0T} on the machine tool with active compensation with second test cycle for nozzle height 50 mm, not compensated E_{X0C}

Table 1: Relative reduction of thermal location errors for investigation of cutting fluid influences for both test cycles and the case of cutting fluid outlet position on the left side of the table for the quality criterion arithmetic mean (M_W)

Error		test cycle	2. test cycle	Left side
E_{Y0C}	Improvement [%]	85.5	86.7	92.7
E_{R0T}	Improvement [%]	68.8	62.5	77.3
E_{Z0T}	Improvement [%]	65.6	66.4	83.1
E_{A0C}	Improvement [%]	60.1	64	32.4

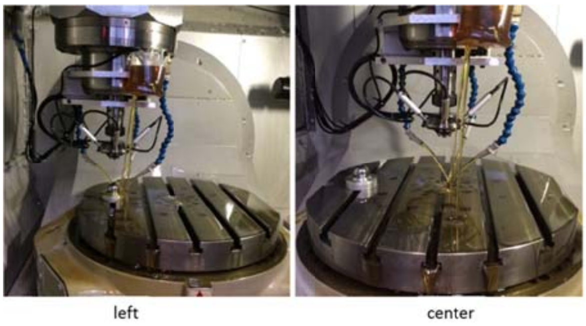

Figure 8: Measurement nest and fluid supply position left and center during the test cycle

To test the robustness of the model, the cutting fluid outlet is moved to the left side of the machine table (see figure 8) that most of the cutting fluid is spread to the surrounding structure on the left. The first test cycle is performed with active compensation. In table 1 the right column shows the relative reduction of the thermal location errors for the situation of the fluid outlet on the left table side. To the fact, that the influence of the cutting fluid is reduced in the same way as of a centered outlet, it is shown that the robustness of the model is sufficient for different cutting fluid outlet positions and heights.

4 COMPENSATION OF CUTTING FLUID INFLUENCES USING A PHENOMENOLOGICAL COMPENSATION MODEL

A system of differential equations according to [14] is used for modeling the thermal errors on machine tools. The structure of the differential equation for a single thermal error y provoked by one single thermal load u is:

$$\frac{dy}{dt} = p_1 \cdot y + p_2 \cdot [u(t) + p_3] \tag{7}$$

$p_1, \ldots p_3$ are constant parameters. p_1 weights the actual thermal error y, p_2 weights the input parameter $u(t)$ and p_3 is a zero balancing parameter that adjusts the mathematical zero of the equation to the physical system's zero. The parameters $p_{1\ldots3}$ of equation (7) are identified from measurements. As shown in [3], when considering several inputs, as e.g. the environmental temperature change at different points and internal influences, the model can be extended by superposition. To compute the overall thermal location error $\underline{y}_{tot}(t)$ with the inputs environmental temperature change $\underline{y}_1$, cutting fluid influences $\underline{y}_2$ and internal losses $\underline{y}_3$, equation (7) becomes:

$$\frac{d}{dt}\underline{y}_{tot}(t) = \frac{d}{dt}\underline{y}_1(t) + \frac{d}{dt}\underline{y}_2(t) + \frac{d}{dt}\underline{y}_3(t)$$

$$\frac{d}{dt}\underline{y}_{tot}(t) = \underline{\underline{p}}_1 \cdot \underline{y}_1(t) + \underline{\underline{p}}_2\left(\underline{u}_1(t) + \underline{p}_3\right) + \underline{\underline{p}}_4 \cdot \underline{y}_2(t) + \underline{\underline{p}}_5\left(\underline{u}_2(t) + \underline{p}_6\right) + \underline{\underline{p}}_7 \cdot \underline{y}_3(t) + \underline{\underline{p}}_8\left(\underline{u}_3(t) + \underline{p}_9\right) \tag{8}$$

In equation (8) the input $\underline{u}_1(t)$ is the environmental temperature, $\underline{u}_2(t)$ is the axis cooling power, and $\underline{u}_3(t)$ is the cutting fluid temperature. The parameter set $\underline{\underline{p}}_1, \ldots, \underline{p}_9$ are derived from different measurements. First, the model for environmental influences is developed and the parameters $\underline{\underline{p}}_1$, $\underline{\underline{p}}_2$ and $\underline{p}_3$ are computed. With these derived parameters the machine tool is compensated against environmental influences and the next input is investigated, either the cutting fluid influences or the thermal errors arising due to internal losses so that the parameters $\underline{\underline{p}}_4$, $\underline{\underline{p}}_5$ and $\underline{p}_6$ resp. $\underline{\underline{p}}_7$, $\underline{\underline{p}}_8$ and $\underline{p}_9$ are computed. The parameters of the model cannot be evaluated in a single measurement run as the model computes the thermal location errors $\underline{y}_i(t)$ with respect to one input parameter $\underline{u}_i(t)$ at a time.

Figure 8 shows the location errors induced by cutting fluid, internal load and environmental influences on a compensated machine tool compared to an uncompensated machine tool. The internal load is induced by a randomly generated pattern of the rotational speed of the rotary axes of the Mori Seiki NMV 5000 DCG.

As measurements for a single influence take several days an overall measurement time of about 10 days is required to get the full compensation model for the rotary/swiveling axis unit with this approach. To overcome this, a second approach, what requires only one measurement cycle, is developed. With simultaneous estimation, the amount of unknown model parameters is reduced. More importantly the measurement time is drastically decreased. With one randomly generated measurement cycle the model parameters required for full compensation of environmental influences, thermal errors induced by internal losses and influences of the cutting fluid on the thermal deviations of the rotary axis can be obtained.

Equation (8) can be reduced to:

$$\frac{d}{dt}\underline{y}_{tot}(t) = \underline{\underline{p}}_1 \cdot \underline{y}_{tot}(t) + \underline{\underline{p}}_2 \cdot \underline{u}_1(t) + \underline{\underline{p}}_3 \cdot \underline{u}_2(t) + \underline{\underline{p}}_4 \cdot \underline{u}_3(t) + \underline{p}_5 \qquad (9)$$

$\frac{d}{dt}\underline{y}_{tot}(t)$ represents the actual thermal location error change, $\underline{y}_{tot}(t)$ is the actual thermal error, $\underline{u}_1(t)$ is the input parameter for the environmental temperature change, $\underline{u}_2(t)$ is the input parameter for the rotary axis thermal load, $\underline{u}_3(t)$ is the input parameter for the cutting fluid temperature change, $\underline{\underline{p}}_1$, $\underline{\underline{p}}_2$, $\underline{\underline{p}}_3$, $\underline{\underline{p}}_4$ and $\underline{p}_5$ are constant parameters. The parameter $\underline{\underline{p}}_1$ is weighting the actual thermal error, influencing the error change, $\underline{\underline{p}}_2$, $\underline{\underline{p}}_3$ and $\underline{\underline{p}}_4$ are weighting the inputs and $\underline{p}_5$ is zero balance factor.

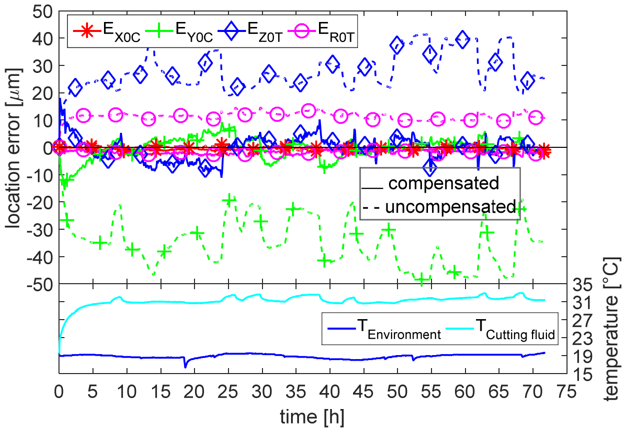

Figure 8: Measured thermal location errors E_{X0C}, E_{Y0C}, E_{Z0T} and E_{R0T} induced by cutting fluid, internal load and environmental influences on compensated machine tool using model of equation (8)

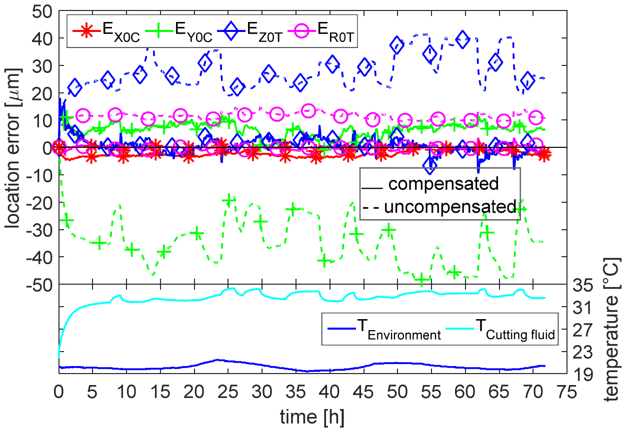

Figure 9: Measured thermal location errors E_{X0C}, E_{Y0C}, E_{Z0T} and E_{R0T} induced by cutting fluid, internal load and environmental influences on compensated machine tool using model of equation (9)

Figure 9 illustrates the measured thermal location errors under the influence of cutting fluid, internal losses and environmental influences on a compensated machine tool using the model of equation (9). With the approach the required measurement time is reduced to 72 hours. Table 3 compares both models for three quality criteria: peak value, mean value and quadratic deviation from mean value. the R-Test discrete measurements show that with both approaches similar results are derived. It is illustrated that the procedure with a single measurement to estimate the model parameters is sufficiently accurate to compensate the major thermal machine tool errors.

Table 3: Thermal location errors for investigation of rotary axis relative reduction for the quality criterion peak value (P_V), arithmetic mean (M_V), the quadratic deviation to the mean value (Q_M), (8) is related to the model of equation (8), (9) is related to the model of equation (9)

Error		**P_V [µm], [µm/m]**	**M_W [µm], [µm/m]**	**Q_M [µm^2], [µm^2/m^2]**
E_{Y0C}	uncompensated	49	-35	73
	compensated (8)	25	-0.2	15
	compensated (9)	16	6	6
	improvement (8) [%]	49	99	80
	improvement (9) [%]	69	82	91
E_{Z0T}	uncompensated	42	28	44
	compensated (8)	29	-0.3	16
	compensated (9)	27	1	8
	improvement (8) [%]	30	99	64
	improvement (9) [%]	34	97	81
E_{R0T}	uncompensated	15	11	1.7
	compensated (8)	5	-2	0.5
	compensated (9)	7	-0.1	0.5
	improvement (8) [%]	65	84	71
	improvement (9) [%]	56	99	73
E_{A0C}	uncompensated	38	16	80
	compensated (8)	41	-4	62
	compensated (9)	125	-12	63
	improvement (8) [%]	-9	75	23
	improvement (9) [%]	-232	27	21

5 CONCLUSION

The Mori Seiki NMV 5000 DCG of IWF is used to investigate the influences of cutting fluid to the thermal behavior of the machine tool. A strong influence of the cutting fluid is illustrated. The arising temperatures measured are higher when cutting fluid is supplied to the process zone. In consequence, the measured thermally induced machine tool errors increase.

Two different models to compensate the influences of cutting fluid on five axis machine tools are presented. The first approach uses a thermobalance model to predict the thermal errors arising by changes in the environmental temperatures, internal losses and cutting fluid temperatures. This model is capable for online compensation. Up to 90 % of the arising thermal location errors of the machine tool can be compensated with the approach.

The second approach uses a phenomenological gray box model consisting of a system of differential equations for predicting thermal location errors arising by changes in the environmental conditions, by temperatures influencing the machine tool structure, by running the rotary axes and by changes of the cutting fluid temperature. Conventionally each influence is investigated separately. It is illustrated that with this approach more than 90 % of the arising thermal errors can be compensated. A disadvantage of the approach is the required measurement time of about 10 days necessary to derive all model parameters for a fully compensated rotary/swiveling axis unit of the machine tool. The system of differential equations is therefore modified to a reduced model in a way that all model parameters can be derived simultaneously. It is illustrated that the measurement time is drastically reduced to about one third without significantly losing precision of the compensation model. Again, more than 90 % of the arising thermal errors can be compensated.

6 FURTHER STEPS

In the presented work thermal machine tool errors due to internal losses, changes in environmental conditions and changes of the cutting fluid temperature are compensated with models derived from measurements. As due to wear etc. the thermal behavior of machine tools can change over time, it is necessary to control and recalibrate the models occasionally. To be able to perform the measurements without production interruption, on-machine measurements are currently under development. The existing models will be extended with an iterative model updating algorithm in the next steps.

To validate the different compensation models during real milling processes a thermal test piece will be used. The current thermal test piece introduced to MTTRF in 2014 [11] is optimized based on finite element simulations.

For a complete understanding of the heat propagation in the machine tool, a thermo-energetic model of the Mori Seiki NMV 5000 DCG is currently under development. The model is capable to display all relevant energy, fluidic and temperature flows of the machine tool in defined stages. Further, the model is capable to compute the temperature in the fluidic elements of the machine tool after each component and the interaction of the fluid temperature with the surrounding structure.

In future a complete finite element method based physical compensation approach is planned to be developed with MTTRF machine tool. For this IWF request CAD data of the machine tool.

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