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REAL-TIME COMPENSATION OF MACHINE TOOL THERMAL ERRORS INCLUDING CUTTING PROCESS

The challenge to be addressed by this paper is to extend the common machine tool thermal compensation models considering only internal heat sources to include the effects of the cutting process. Although real-time software compensations of thermal errors exist, the majority of these models only presume machine tools under load-free rotation of the main spindle without any reference to rough machining. The machining process is completely neglected in spite of the fact that it represents a significant heat source and causes workpiece inaccuracy. This paper presents a real-time compensation of three-axis vertical milling centre thermal errors including the cutting process effect. The simulation is based on dynamic modelling using transfer functions. The model was implemented into a standard CNC controller of a three-axis vertical milling centre to compensate for thermal errors in real time. The inputs of the compensation algorithm are the spindle rotational speed, the 5 temperatures of the machine structure and spindle power. A reduction of thermal errors achieved by using the new approximation TF model including cutting process impact is up to 79% for steel cutting tests with different cutting conditions.

1. INTRODUCTION

Machine tool designers endeavour to achieve high workpiece accuracy, which is one of the main customer requirements. There are many causes of workpiece inaccuracy. Thermal errors are the most dominant causes and have been affecting the accuracy of production machines (workpieces) for a long time. It is a well-known fact that more than 50% of the overall geometric errors on machined workpieces are due to effects of temperatures [1],[2],[3]. The relative displacement between the tool center point (TCP) and workpiece cannot be monitored by any linear or angular encoders during the cutting process and leads to an unavoidable workpiece error.

Besides the static and dynamic deformation properties, machining accuracy of a machine tool is strongly affected by its thermo-elastic behaviour as mentioned above.

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As machine inaccuracy is a major source of workpiece errors, control of machine error sources is critically important [4]. Moreover, due to scientific achievements in the static and dynamic field of research and due to an increasing interest in faster, more precise, ecology-minded, energy-efficient and cost-saving production by the metal-working industry, the thermo-elastic machine behaviour is considered to be of particular importance. The thermal impact on machining accuracy continuously increases [5].

Challenges for machining include greater and greater material removal rates (with rising total electrical power of conventional machine tools) coupled with an increase in the use of difficult-to-machine materials, as well as environmentally-friendly dry or minimum quantity lubrication (MQL) machining. These trends lead to a large (and variable) heat input into the machine structure [6] causing thermo-elastic displacements of the machine tool, the tool, the workpiece and the clamping devices. Therefore, this topic is still the focus of latest research activities [7] which should subsequently lead to practical industrial application. The interest of the manufacturing industry in this topic can also be seen in the latest international standards. In the last two decades a number of international standards have been developed, comprising measurement rules and performance parameters, to assess the thermal behaviour of machine tools [8],[9],[10]. However, these standards take into consideration primarily thermal behaviour under no load or finishing conditions.

2. STATE OF THE ART

Thermally induced displacements at the TCP of a machine tool structure cannot be sufficiently eliminated by design concept and/or by temperature control without high additional costs. On the contrary, indirect (software) compensation of thermally induced displacements at the TCP is one of the widely employed techniques to reduce machine tool thermal errors due to its cost-effectiveness and ease of implementation.

Over the past several decades, researchers or machine tool producers have investigated many strategies to establish models of thermally induced displacements at the TCP, e.g. multiple linear regressions (MLR) [11],[12],[13],[14],[15], artificial neural networks [16],[17],[18], transfer functions (TF) [19],[20],[21],[22],[23], etc. (for more details see [24]).

Ordinarily, thermal error models are based on measured auxiliary variables [25]. Here, in most cases, temperature values of representative points of the machine structure, environmental temperatures or spindle speed are used for calculation of the resulting thermally induced displacements at the TCP. The principle of the indirect compensation method is shown in Fig. 1.

Although real-time software compensations of thermal errors exist and machine tool producers often present them at international fairs, these compensations have a number of serious drawbacks. The majority of these models only presume machine tools under load-free rotation of the main spindle (air cutting) without any reference to rough machining. One of the presumed causes is that measurement procedure described in the standards is used for machine tools under no load or finishing conditions as mentioned above. The machining

process is completely neglected in spite of the fact that the machining process represents a significant heat source and consequently an essential cause of workpiece inaccuracy.

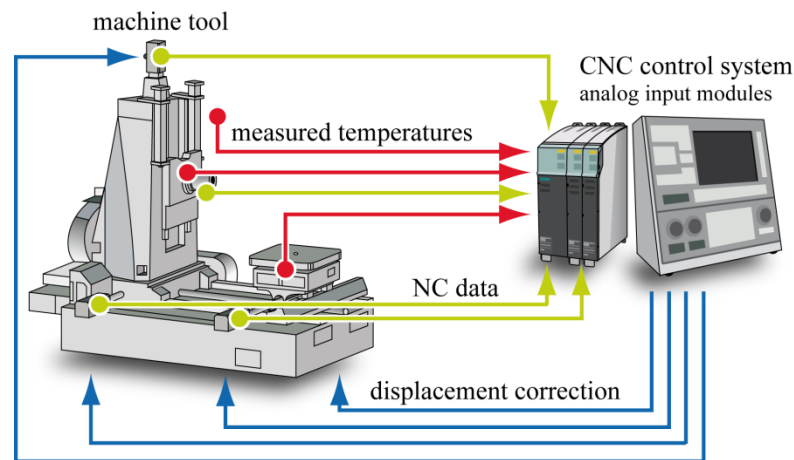


Fig. 1. Scheme of the indirect compensation method of machine tool thermal errors

Compensation of the thermal distortion of a machine tool by using indirect compensation methods based on measurement under no load makes sense for finishing or low power processes. Rough machining requires high torques and much electrical power, which dissipate in heat. The result is obvious: due to the strong heat development of the spindle, even at a low speed level, the TCP displacement is high [25].

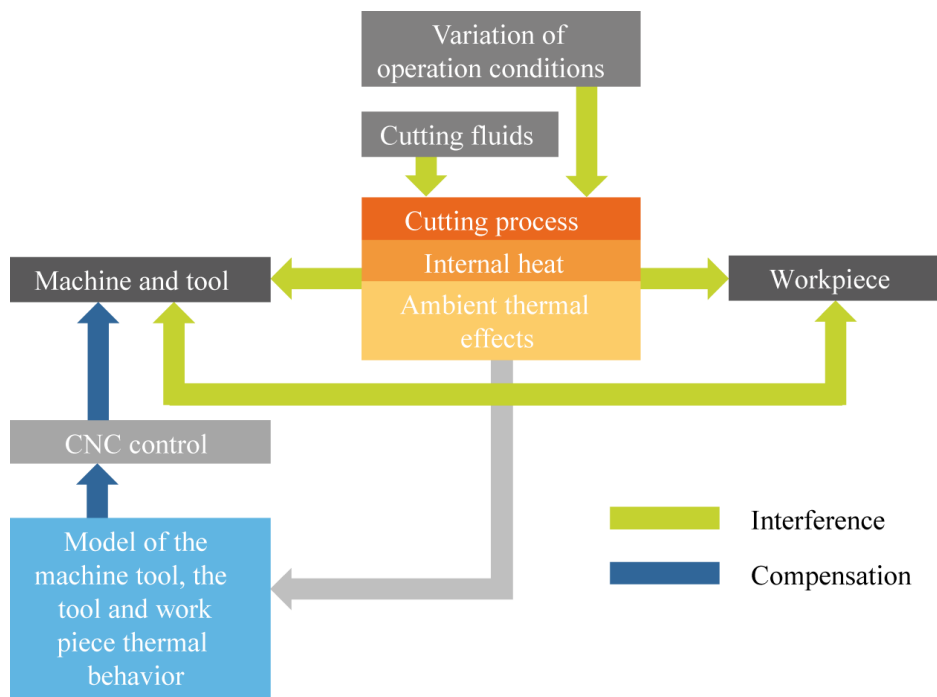


Fig. 2. Complex approach to thermal compensation modelling including cutting process

However, the relationship between the thermal load of the machine and the thermal drift of the cutting process is very complex [26]. The high complexity of the machine tool – tool – workpiece system thermal behaviour (see Fig. 2) results in difficulties how to address the phenomenon by robust and reliable approaches, which could successfully be implemented in the machine tool real-time control.

Generally, there are two main aspects of the cutting process that affect machining accuracy.

Firstly, power of the main spindle and feed drives (electric current and consequently generated heat) increase during the cutting process, especially in the case of rough machining. Thermal distortion under the spindle load condition was investigated using a stressing unit in [27]. Forces are simulated with a hydraulic pump, the magnitude of the load depends on the oil pressure and is controlled by a choke, which is regulated manually. Subsequently, a robust compensation of thermo-dependent machine tool deformations due to spindle load in consideration of rough machining was developed based on tests with the stressing unit [25].

Secondly, the cutting process itself is a very problematic heat source. A certain amount of heat generated by the cutting process is always transferred into the tool, machined workpiece, chips and coolant. Further, it dissipates through the tool chuck into the spindle, and through the workpiece and the clamping system into the machine table. It is very difficult to determine heat partition ratios of these components (tool, the workpiece, the clamping devices, chips and coolant) depending on cutting conditions [28]. From machining tests carried out under different parameters on a three-axis vertical machining centre it was observed that depending upon the material removal rate, the cutting parameters used etc., the X-axis positioning error varied. It was also shown that the thermal error rapidly increases at the moment when wet cutting with a coolant becomes dry cutting [29]. The temperature rise of the spindle housing and the thermal growth of the spindle under four different air cutting and cutting conditions were tested in [11]. The result showed that the prediction accuracy of the air cutting model is unacceptable in real cutting applications.

Resulting from the state of the art, the compensation method of machine tool thermal errors should include cutting process effects to ensure robustness of the compensation algorithm during real cutting conditions. In [22],[23] was presented a general approach to fast and robust dynamic modelling of thermally induced displacements at the TCP of a machine tool based on TFs. This approach was successfully applied to 3 different machine tool structures [30]. The tested TF models proved their ability to significantly reduce thermal errors at the TCP independently of the machine tool structure. However, developed models were designed based on tests under load-free rotation. The presented work is the beginning of an extension of the TF model to the real cutting process impact.

3. COMPENSATION OF THREE-AXIS VERTICAL MILLING CENTRE USING TF

Software compensation using TFs represents dynamic modelling of thermally induced displacements at the TCP of a machine tool. These models consider temperature history

of the input variables. However, the input of the estimated TF can also be NC data such as spindle speed, effective power, electric current, torque or feed rate or NC data in combination with temperature inputs [19],[32],[33].

In [30], a thermal errors TF model of a vertical milling centre (built on a supporting C-shaped frame as shown in Fig. 3) was presented. The developed TF model for the vertical milling centre describes only the spindle rotation under load-free rotation (LC 200 Kessler spindle) and ambient temperature as the causes of the overall thermal errors at the TCP. The remaining inner heat sources were neglected in [30]. The inputs of the compensation algorithm are the spindle rotational speed n and 3 temperatures: temperature near the front spindle bearing assembly ($T_{sp-bearing}$), spindle motor temperature ($T_{sp-motor}$), and ambient temperature (T_{amb}) see Fig. 3.

The model was divided into several revolution levels, which permits fine tuning of the nonlinear convection component [31].

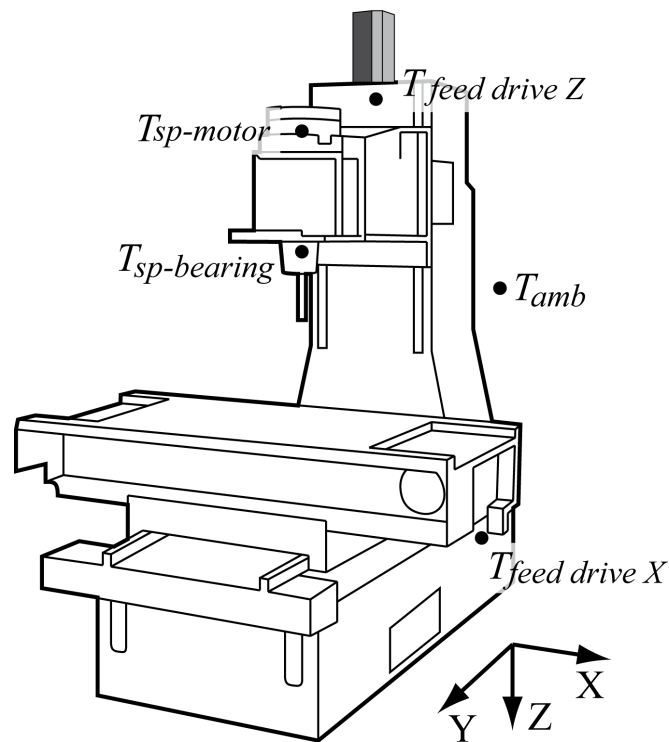


Fig. 3. Resistance thermometers on a 3-axis vertical milling centre built on a supporting C-shaped frame

3.1. THERMAL ERRORS MODEL EXTENSION TO THE IMPACT OF LINEAR MACHINE AXIS MOVEMENTS

Generally, modelling using TFs enables easy superposition of the causes of thermal errors at the TCP. Thus, the developed compensation model was extended to include the impact of linear machine axis movements in X and Z direction (Y direction was neglected due to the marginal impact on overall thermal displacements at the TCP).

The machine tool was equipped with 80 resistance temperature detectors. Further, eddy current sensors were employed for noncontact sensing of displacements at the TCP (in directions X , Y and Z) according to ISO 230-3 [10], namely tests for thermal distortion caused by moving linear axes (X and Z).

In general, the selection of temperature inputs to the TF model is very straightforward. It is ordinarily the closest measured temperature to the heat sources/sinks whose contribution to the overall thermal displacements should be determined by TF. Therefore, additional 2 temperatures close to the modelled heat sources were chosen as inputs to the part of the TF model which describes the impact of the machine axis movement in X and Z direction (temperatures close to the bearings of feed drive X and Z axis denominated as $T_{\text{feed drive } X}$ and $T_{\text{feed drive } Z}$, see Fig. 3). Figure 4 depicts time behaviour of temperatures which are used as inputs of the extended TF model during experiments which partly served for model calibration and partly for verification of the extended air cutting TF model. The experiments include spindle speed rotation (the grey curve in Fig. 4, the revolutions of the spindle were 6,000 rpm) combined with various feed rates in the X and Z machine axes (maximum feed rates were 15 m/min) as shown in the upper part of Fig. 4.

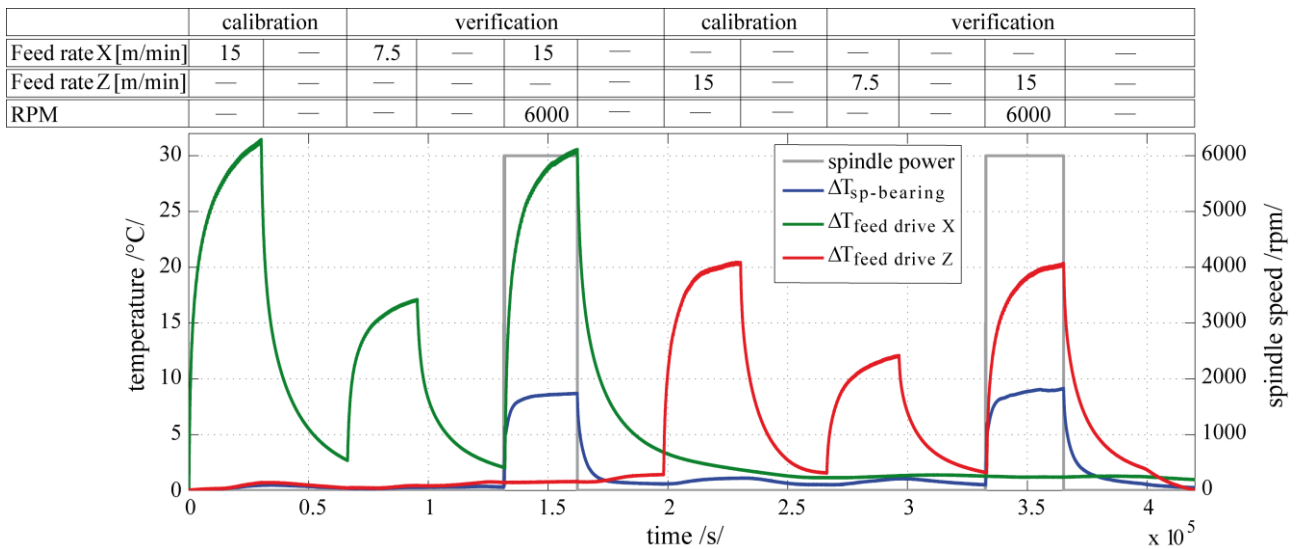


Fig. 4. Temperature time behaviour (inputs of the estimated TFs) with operating conditions during the experiment

The TF model is built based on the regressive methods. TFs were estimated via ARX (autoregressive with external input) or OE (output error) model in software Matlab/Simulink[®] [34] as was presented in previous scientific work e.g. [23],[30].

Generally, the differential form of the TF in the time domain has the following formulation:

$$y(k) = \frac{u(k-n)a_n + \dots + u(k-1)a_1 + u(k)a_0 - y(k-m)b_m - \dots - y(k-1)b_1}{b_0} \quad (1)$$

where: $u(k)$ is the TF input vector in time domain, $y(k)$ the output vector in time domain, a_i are weight factors of TF input, b_i are weight factors of TF output and $k-n$ means the n -multiple delay.

The approximation quality of the simulated thermally induced displacements at the TCP behaviour is expressed by the *fit* (%) value (2). This value expresses the percentage of the output variations that is reproduced by the model [34]:

$$fit = \left(1 - \frac{\|Y - Y_{HAT}\|}{\|Y - \bar{Y}\|} \right) 100 \quad (2)$$

where: the Y value in (2) means the measured output (thermal displacement), Y_{HAT} is the simulated/predicted model thermal displacement (by TF model) and \bar{Y} in (2) expresses the arithmetic mean of the measured output.

The error of approximation is also expressed by *residue* (μm):

$$residue = Y - Y_{HAT} \quad (3)$$

Residue represents the fictive thermal displacements at the TCP (thermal error) obtained after implementing the compensation algorithm into the machine tool control system.

The extended TF model which describes thermal influences caused by spindle rotation under no load and the Y and Z axes movement will be denominated as AC TF model in the following text (AC denominates air cutting). The graph in Fig. 5 depicts the residual errors in Z directions obtained by AC TF model (*residue_Z*, the blue curve, *fit* according to equation (2) is 84%), AC TF model prediction of thermally induced displacements in Z directions at the TCP (the grey curve) and thermally induced displacements in the Z direction without any compensation (the black curve, measured thermal displacements in Z direction) during the experiment with operating conditions according to Fig. 4.

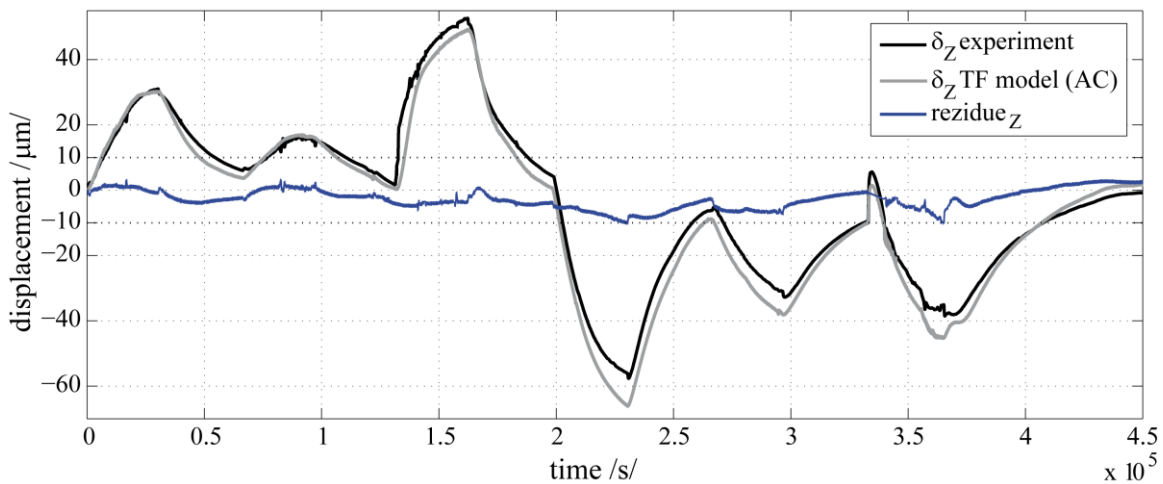


Fig. 5. Residual errors in Z directions obtained by the AC TF model (the blue curve), AC TF model prediction of thermally induced displacements in Z direction at the TCP (the grey curve) and thermally induced displacements in Z direction at the TCP without any compensation (the black curve)

4. IDENTIFICATION AND SIMULATION OF THE IMPACT OF THE CUTTING PROCESS ON THERMAL ERRORS

The impact of the cutting process on overall thermal displacements at the TCP is investigated in this section. In order to implement the cutting process influence into the existing simulation model based on TF, a series of technological tests was carried out.

4.1. EXPERIMENTAL SETUP

Face milling was chosen as the basis for measurement of cutting process influence using a 5 edge cutter (SANDVIK CoroMill[®] 245, R245-063Q22-12M; see Fig. 6). Medium-carbon steel 1.0503 (DIN C45) was applied as the workpiece material for the following experiments. All technological tests were carried out without coolant (dry machining) according to the latest worldwide trend to save the environment and production costs.

There was an effort to keep spindle power almost constant during all technological tests, which take approximately 4 hours. Cutting process with almost constant spindle power was stopped only due to measurement cycles to acquire thermal displacements. Two 5 edge cutters of identical type were employed for cutting tests. If the spindle power increased due to tool wear during the cutting test, the cutter was replaced by the new one.

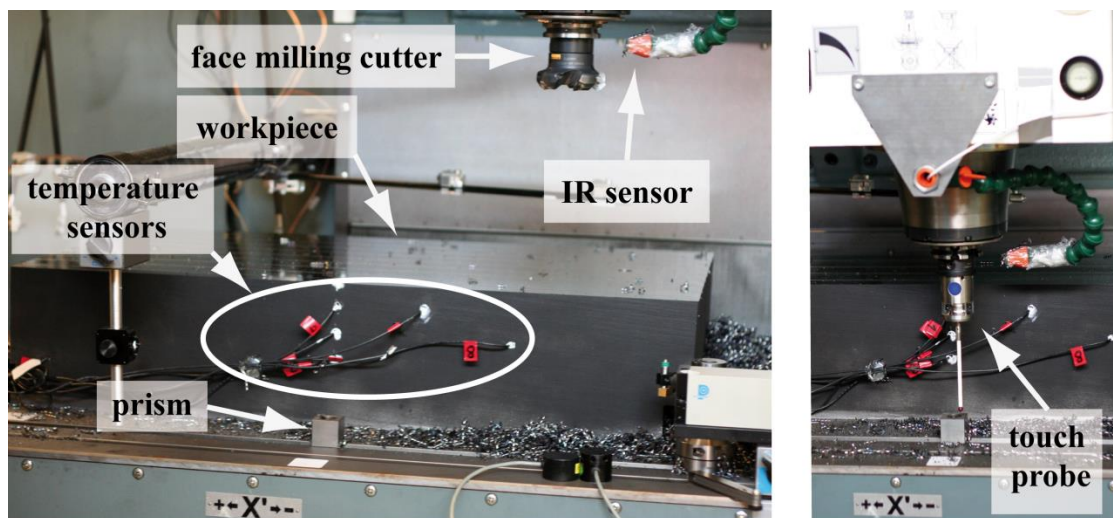


Fig. 6. Experimental setup

Thermal displacements were measured using workpiece touch probe approximately in 15 minutes interval. Firstly the cutter was replaced by the touch probe to facilitate the measurement. Thereafter the workpiece touch probe sensed an edged small prism placed in front of the workpiece (Fig. 6 left) in X , Y and Z directions (see Fig. 6 right). Measured

thermal displacements were stored in text file. Finally the workpiece touch probe was replaced by the cutter and machining started. A measurement cycle took approximately 5 minutes. List of cutting conditions for air cutting and steel cutting is summarized in Table 1.

Table 1. List of cutting conditions for the air cutting and steel cutting

Number of test	Type of test	Depth of cut (mm)	Spindle speed (rpm)	Feed rate X (mm/min)
1	Low-speed - air cutting	0	600	1050
2	Steel cutting ~ 1.5 kW	1	1011	1213
3	Steel cutting ~ 3 kW	1.4	600	1050
4	Steel cutting ~ 4.5 kW	1.25	1076	1345

Besides temperatures of the machine structure, ambient temperatures and thermal deformations at the TCP, NC data such as effective power, electric current, torque, feed rate, etc., were measured during the tests. Profibus communication between the machine controller (Heidenhain, iTNC 530) and the programmable automation controller (PAC) NI CompactRIO produced by National Instruments was used for this purpose

PAC NI CompactRIO was used for data acquisition (sampling rate is 1seconds) and also for thermal error compensation (control) in the next stage of developments.

Moreover, the thermal field of the workpiece was measured using an infrared camera and several RTD sensors placed inside the workpiece. The reason was to evaluate thermal deformation of the workpiece. However, this topic is not covered in the developed compensation model and therefore it is not discussed in this paper.

Non-contact measurement of the tool temperature was carried out using the Optris CT-SF15-C1 infrared sensor, which was aimed at the upper part of the tool (see Fig. 6). The reason was to evaluate thermal displacement of the cutter itself. However, this topic is not covered in this paper as well.

Thermal displacements measured by workpiece touch probe (stored in text file) are combined with data measured by PAC NI CompactRIO during data processing (thermal error model development stage; see Chapter 4.3).

4.2. VERIFICATION OF AIR CUTTING TRANSFER FUNCTION MODEL (AC TF MODEL)

The developed AC transfer model was tested during test 1 (see Table 1). The operating conditions except depth of cut (i.e. spindle speed and feed rate X) of which were adjusted as a 3 kW cutting test (test 3, see Table 1). The discussed AC TF model was calibrated during different air cutting tests, see [30] and also Chapter 3.1 for details.

Figure 7 (left) shows the behaviour of AC TF model inputs (temperatures, spindle power) during air cutting test (test 1, see Table 1).

Figure 7 (right) depicts a comparison of measured thermal deformation in Z direction (the black curve) with thermal deformation prediction of the applied AC TF model (the blue curve) during the air cutting test 1.

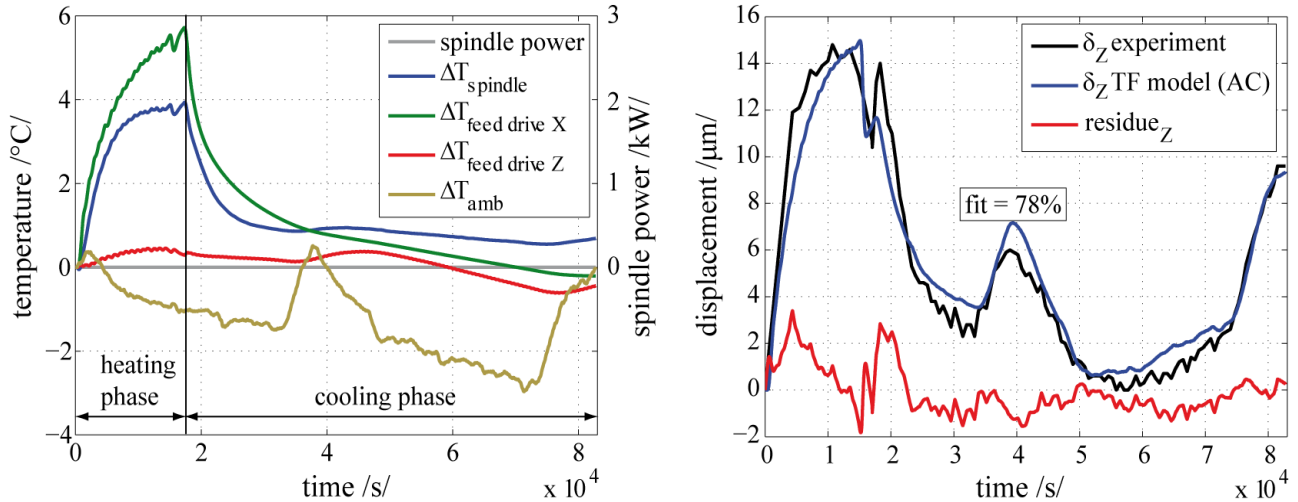


Fig. 7. Inputs into the approximation model during air cutting test (left) and thermal deformation of Z axis during air cutting (spindle speed and feed rate X were adjusted as 3 kW cutting test) and results of simulations

Achieved reduction of thermal errors (residue_z depicted by the red curve) is up to 78% (fit value according to equation (2)) in comparison with the uncompensated state.

4.3. SIMULATION OF THE IMPACT OF THE CUTTING PROCES

The development of a TF model including the impact of the cutting process CP (CP denotes cutting process) was performed as follows:

(1) The TF AC model was applied on 3 kW cutting test data (test 3, see Table 1). Inputs into the model (temperatures, spindle power) are depicted in Fig. 8 (left).

(2) The calculation of the residue_z between the measured and simulated data is used as a response in an identification process of cutting process influence, see the red curve in Fig. 8 (right). The mean of the spindle power was used as an excitation, see the grey curve in Fig. 8 (left). The TF was identified using System Identification ToolboxTM in Matlab[®] software. The result of the cutting process identification is shown in Fig. 8 (right) by the yellow curve δz TF model (CP denotes cutting process), fit is 86%.

(3) The resultant approximation is calculated by superposition of air cutting influence (AC) and cutting process (CP) impact as depicted by the green curve in Fig. 8 (right), black curve represents measured thermal deformation of Z axis during 3kW cutting test (test 3), fit is 92%.

The TF model of thermally induced displacements at the TCP including the cutting process was verified on executed steel cutting tests according to Table 1.

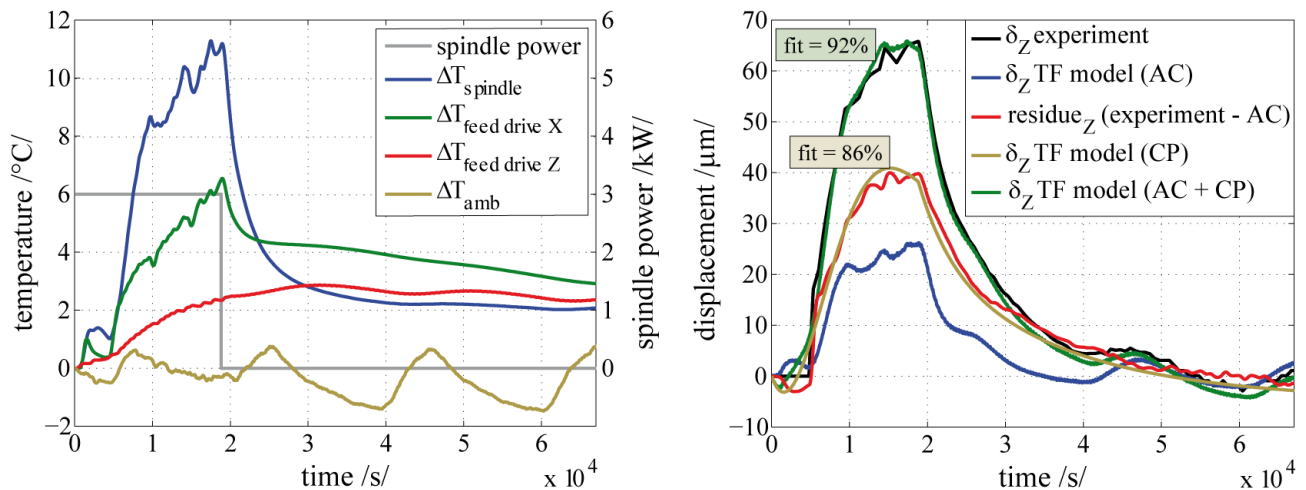


Fig. 8. Inputs into the approximation model during 3 kW cutting test performed with a 5 edge cutter (left), thermal deformation of Z axis during 3 kW cutting test (performed with a 5 edge cutter) and results of simulations

The application of the identified TF model including cutting process (AC+CP model) on a 1.5 kW cutting test (test 2 with cutting parameters according to the Table 1), for example, is shown in Fig. 9 (left). A reduction of thermal errors achieved by using the new approximation model (AC+CP) is up to 65% (*fit*). Another verification of the identified TF model including cutting process (AC+CP model) on a 4.5 kW cutting test (test 4; see Table 1) is shown in Fig. 9 (right). A reduction of thermal errors achieved by using the new approximation model is up to 79% (*fit*) in this case.

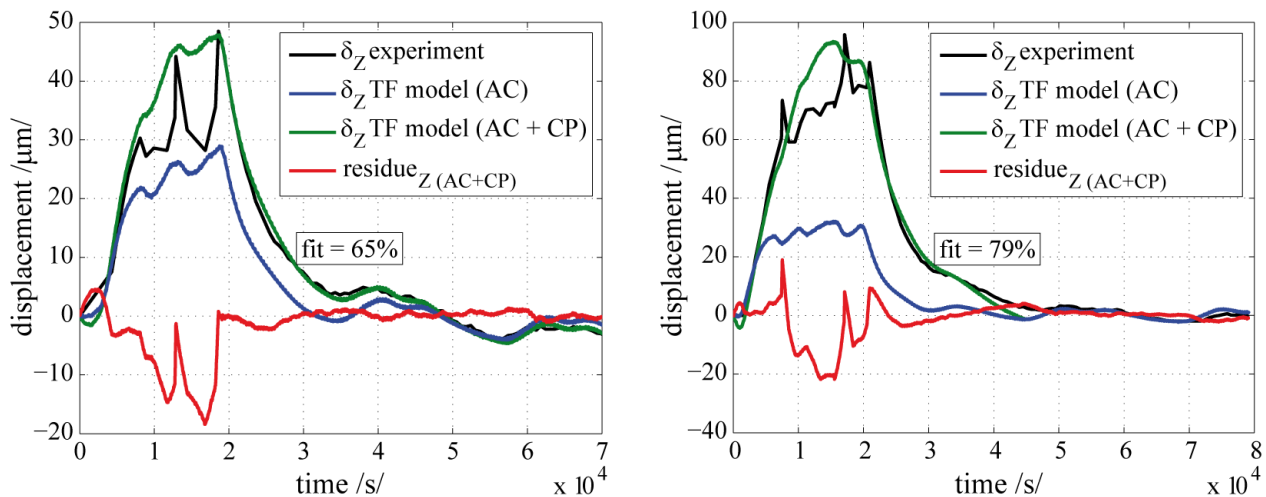


Fig. 9. Thermal deformation of Z axis and results of simulations during 1.5 kW cutting test 2 (left) and during 4.5 kW cutting test 4 (right)

The approximation of the air cutting compensation model (AC) on both cutting tests (1.5kW and 4.5kW) is depicted by the blue curves in Fig. 9 (left and right). The former represents low power processes (finishing condition), the AC compensation model still

gives good results. On the contrary, the latter represent rough machining, the AC compensation model estimation of thermally induced displacements in Z direction at the TCP is very poor as depicted by the blue curve in Fig. 9 (right) in comparison with the experimental results, see the black curve in Fig. 9 (right). The error of approximation expressed by $residue_z$ between the measured and simulated data using AC compensation model reaches even more than 50 μm .

5. SUMMARY

Firstly, the compensation model of vertical milling center thermal errors was designed based on tests according to international standards which presume machine tools under load-free rotation of the main spindle to assess the thermal behaviour of machine tools caused by spindle rotation under no load (see [30]). Secondly, the air cutting compensation model was extended to include the impact of linear machine axis movements in X and Z direction (AC TF model, see Chapter 3.1).

In order to implement the cutting process influence into the existing air cutting simulation model based on TF, a series of technological tests were carried out. Subsequently, a robust compensation of thermally induced displacements at the TCP due to the complex cutting process impact was developed based on performed steel cutting tests (CP TF model).

Next, both models (AC and CP model) are superposed. Finally, the TF model including cutting process impact was implemented into a standard CNC controller of a vertical milling center to compensate for thermal errors at the TCP in real-time. The inputs of the compensation algorithm are the spindle rotational speed, 5 temperatures of the machine structure and the spindle power. A reduction of thermal errors achieved by using the new approximation TF model including cutting process impact is up to 79% (*fit*) for steel cutting tests with different cutting conditions (see Table 1).

Experimental results confirmed the great importance of the cutting process impact on thermally induced displacements at the TCP which should subsequently lead to take into account the cutting process impact to the compensation algorithms of machine tool thermal errors. E.g., the application of the air cutting compensation model on rough machining represented by 4.5 kW cutting test (test 4 in Table 1) demonstrates very poor estimation of thermally induced displacements at the TCP as depicted by the blue curve in Fig. 9 (right) in comparison with the experimental results, see the black curve in Fig. 9 (right).

Therefore, to enhance machine tool precision deteriorated by thermal causes in future, the thermal compensation models should be based on real cutting tests. In other words, compensation algorithms should include cutting process (machining) influence.

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