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Investigation of thermally induced TCP-displacement under load of the machine axes in different areas

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Abstract

As known, thermally induced displacements can cause up to 75% of workpiece errors. To investigate the structural deformation of the machine, Integral Deformation Sensors (IDS) were developed. With these sensors the deformation of machine parts can be measured, and the resulting tool center point (TPC) displacement can be analyzed and predicted by a mathematical model of the machine. This paper focuses on the analysis and prediction of the machine deviation under load of the machine axes in different areas.
As machine tools can hardly be built completely thermically symmetrical, the influence differs, if an axis is only moved in a certain area or along the whole way that the axis can be moved. In this paper, the impact of this fact on thermally induced displacement is investigated in several tests. By doing so, the component deformation is analyzed by IDS. Furthermore, the TCP dislocation is analyzed by modelling it simultaneously by IDS and measuring and the actual displacement using 3D probe. The results show not only the measured displacement of the TCP but also the correct prediction based on the data gathered from the IDS and therefore prove that the compensation method based on the IDS can increase the machines robustness against thermal issues.

Keywords: thermal deformation; thermo-elastic behavior; machine tools; Tool Center Point; correction; modeling

1. Introduction

The producing industry engages efforts to minimize thermally induced workpiece errors which can make up to 75% of geometrical workpiece errors according to Mayr et al. [1]. Countermeasures like air conditioning of production halls or letting the machine perform warm-up cycles before beginning the production are time consuming and cost intensive. Even structural countermeasures like using thermally symmetrical structural parts for the machine can lower but not fully prevent thermal errors. [2] For this reason, research is being carried out into modeling methods to thermally stabilize machine tools. In previous publications it was proven that these methods show promising results. There are multiple methods that are used to predict the thermally induced Tool Centre Point (TCP) displacement. [3, 4] These can be distinguished by the type of source which collects the data that is then used to calculate said placement. [5, 6]

One method uses the machines internal data like shown in [7] to calculate the generated heat and based on that calculate the displacement. This offers the advantage that no sensors need to be placed in or near the working area but the disadvantage that environmental influences can hardly be implemented. Other methods use thermal imaging cameras or temperature sensors that measure the structures surface temperature, then conclude the temperature field in said part and based on this calculate the thermal deformation [8, 9, 10]. Another of these possibilities is directly measuring the thermal deformation of the machines structure and predicting the TCP displacement based on the

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aforementioned measurement. [6, 11] This offers the advantage of eliminating the possible uncertainties associated with other measurement methods when converting the measured quantity, e.g. temperature, since the thermal expansion of the components is measured directly. Using different sensors for the structural deformation measurement such as fiber-bragg sensors [12] or measurement probe, these methods showed a high potential for the thermo-elastic modelling of machine tools. Especially the method based on the thermally stable CFRP rod showed its strengths due to its low cost and high prediction quality [14]. However, the thermo-elastic behavior of machine tools is very complex, since the axis movements and applied machine volume can vary for different workpieces. Thus, this paper presents the application of the IDS for the prediction of the thermo-elastic deviation regarding different machine position and axis load area.

2. Description of measuring method and experiments

The measurement is realized by Integrated Deformation Sensor (IDS). The fundamental design and its functional principle are shown in Fig. 1.

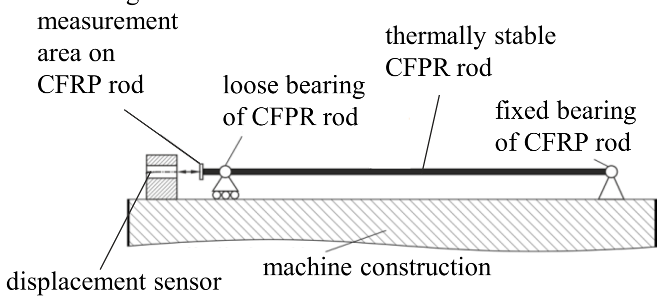

Fig. 1: IDS design

The IDS directly measure the effect of the heat transport mechanisms and therefore also the influence of the environment or the process heat and cooling lubricant by comparing the length of the thermally stable CFPR rod to the length of the machine construction it is directly mounted onto. By knowing the deformation of the main structure of the machine, a mathematical model can predict the displacement of the TCP. A more detailed explanation of this modelling method can be found in [13]. This paper shows the capability of the modelling method described above to predict the TCP-deviation precisely and therefore being able to stabilize the machine tool, even though heat is applied very locally with one axis only moved in a certain part of its range.

The machine the experiments were performed on machine tool which is located at the machine hall of the Fraunhofer IPT. A sketch of the machine including the position of the IDS is shown in Fig. 2.

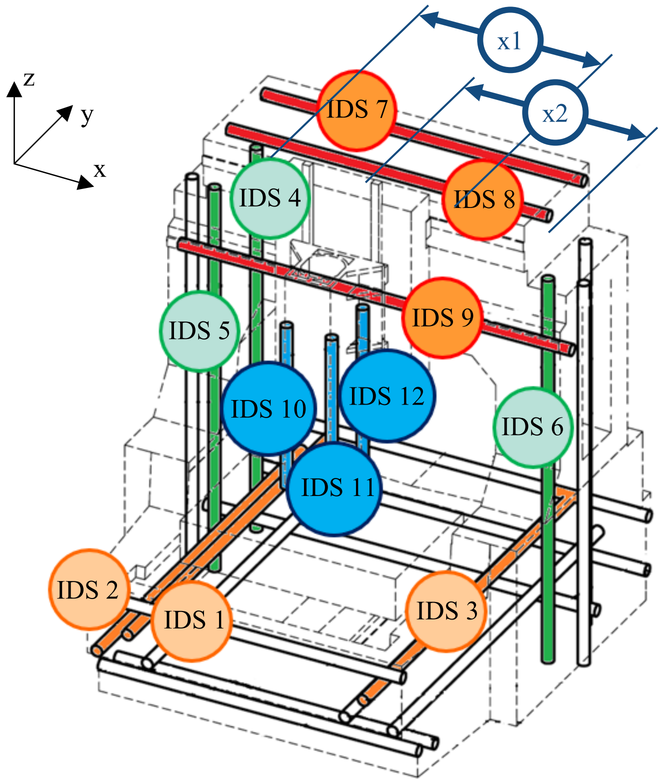

Fig. 2. IDS placement on the demonstrator

To investigate the influence of movements in the different areas of the X-axis three types of experiments were performed on the X-axis. For reasons of clarity in this paper only two of them shall be shown. This abbreviation of the results is acceptable due to the symmetrical structure of the X-axis. Fig. 2 shows the areas in which the axis was moved. The total length of the axes is therefore separated into ranges of 50% of their total length. As Fig. 2 shows this paper will discuss the results of the experiments in which the X-axis was moved in the middle section (x1) and in the right section (x2).

Each experiment started on a different day but at the same time of day to ensure equal starting conditions. The load phase of the experiments is 4-hours long and a 5-hour cooling phase is following afterwards. Within reasonable effort, it is not possible to move the axis for a certain time but only a number of repetitions, therefore the closest value to the 4-hour mark was chosen for the load phase. This explains minor variations regarding the time scale in the figures that show the results later on. The feed rate was set to 100% which means 80 m/min. No cooling lubricant was used for the experiments. The experiments were performed under comparable thermal environmental conditions. To ensure statistically safe results each experiment was repeated five times.

To be able to verify the predicted TCP-deviation based on the IDS measurement, the TCP-deviation was also measured with the measurement probe in the machine tool. This measurement was repeated every 15 minutes during the experiments. The positions of the balls for the measurement are distributed in the working area. Fig. 3 depicts the positions that were chosen for

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this measurement, the colored workspace, and the origin of coordinates.

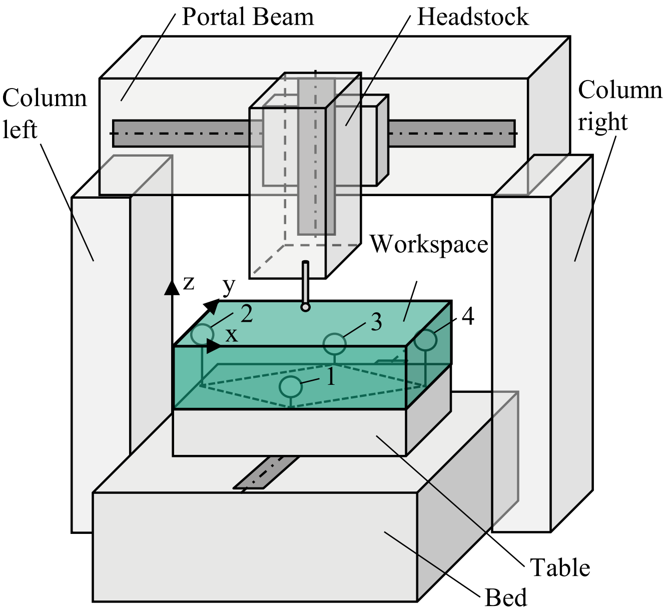

Fig. 3: Positions for the TCP measurement

The numerical values for these positions are listed in Table 1.

Table 1. Positions of the four balls for the measurements

Spatial direction [mm]	x	y	z
Position 1	236.5	52.8	-202.1
Position 2	42.2	298.5	-72.8
Position 3	234.7	494.4	-206.9
Position 4	419.5	304.4	-29

3. Results

This chapter is supposed to show the results of the experiments that are described above. For this purpose, it is first shown what the sensors measure on the example of the IDS mounted to the portal beam. Then the results of the TCP prediction and measurement and finally the remaining error are analyzed.

Firstly, some of the values recorded by the IDS will be shown. The displacement is expected to be the highest at the portal beam (see Fig. 3) for the experiments shown in this paper. Therefore, the measured values of the IDS 7, 8 and 9 are shown in Fig. 4.

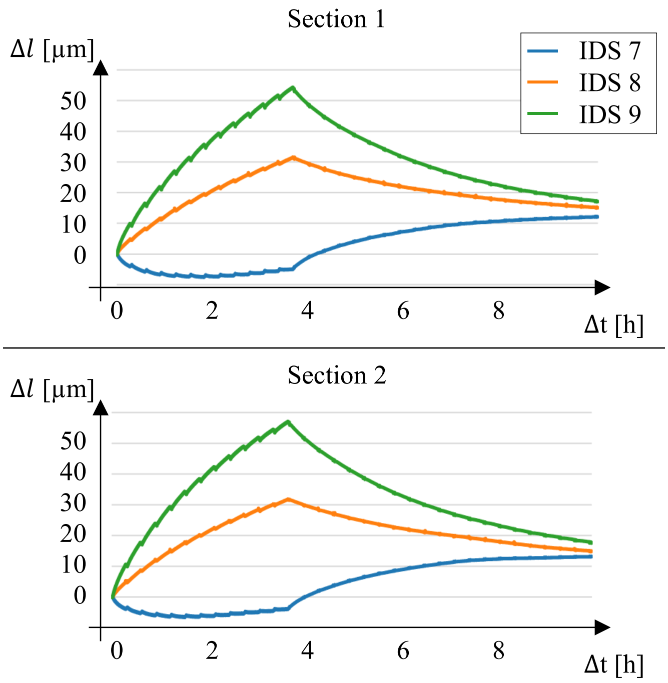

Fig. 4: IDS values measured at the portal beam

As Fig. 4 shows, the graphs show a similar trend over time and the amplitudes differ only slightly by less than 5 µm. Because of the equal loads and therefore heat developed in the portal beam and the thermal symmetry of the portal beam, this result can be expected.

In order to ensure a clear arrangement, the following results will show the results for the middle section (x1) comparing with the section on the right side (x2), both of the X-axis. The following figures show not only the measured TCP-deviations but also the predicted TCP-deviation based on the IDS measurement. This is displayed for position 1 in the upper half and for position 4 in the lower half for reasons of comparison.

One of the similarities these data shows is that the TCP deflection in X-direction is comparatively low for all four points while the highest values are found at point 4. The low deviation in this direction can be explained can be explained by the thermo-symmetrical design of the machine structure regarding the YZ-plane. As the machine is not thermo-symmetrical regarding the XZ-plane the deflection in the Y-direction is significantly higher. Multiple effects come together and result in the movement of the TCP into positive Y-direction for example, the headstocks temperature increases due to the load it could bend around the X-axis and the portal beam also bends because of its increased temperature. The graph showing the progression over time of this can be seen in the results in Fig. 5

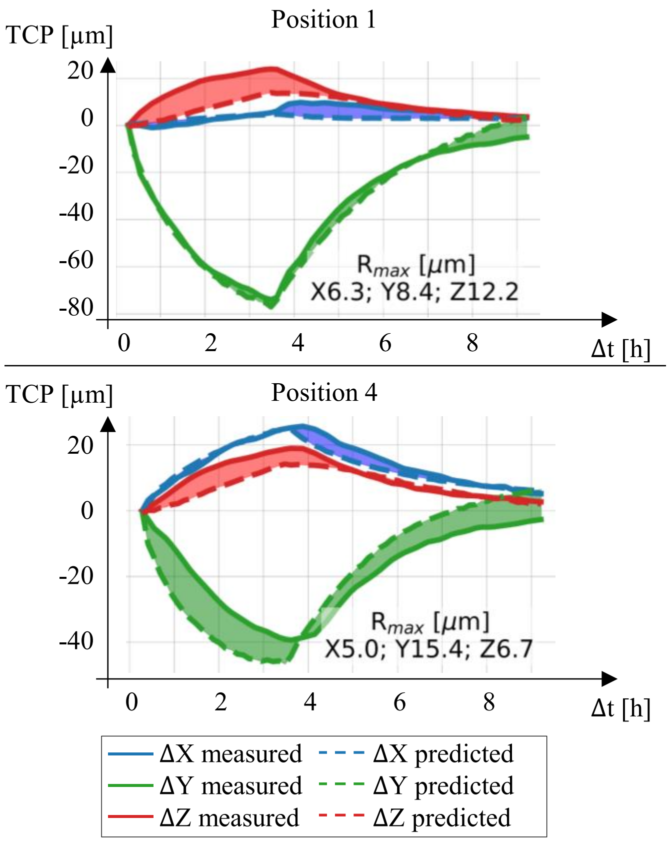

Fig. 5: Comparison of measured and predicted TCP for section 1

It is also striking, that the measured and predicted TCP-deviation for position 1 fit very well on the Y-direction, while there are slight differences for position 4 for this spatial direction. On the other hand, the measured and predicted values in X- and Z-direction are closer to another for position 4 than for position 1. The results for section 1 and 2 show small differences which will be shown by comparing the remaining error between measured and predicted in the following.

Concluding, a comparison of the uncorrected TCP-deviation with the theoretically remaining error after subtracting the predicted TCP-deviation from the measured TCP-deviation shall be shown. These comparisons will be shown for the ball position 1 because the errors are spread more evenly over the axes and the highest error value can be found here. To show this comparison Fig. 6 in the upper half depicts the measured values for the experiment in section 1 with added area of uncertainty for the TCP measurement. In the lower half, the predicted TCP-displacement is subtracted from the measured TCP value, resulting in the remaining TCP error. The following figures also display the area of the prediction uncertainty by the grey area. In [14] Brecher et al. analyzed the uncertainty of the TCP prediction. Here, the uncertainty of the TCP measurement is determined by the specifications given by the manufacturer.

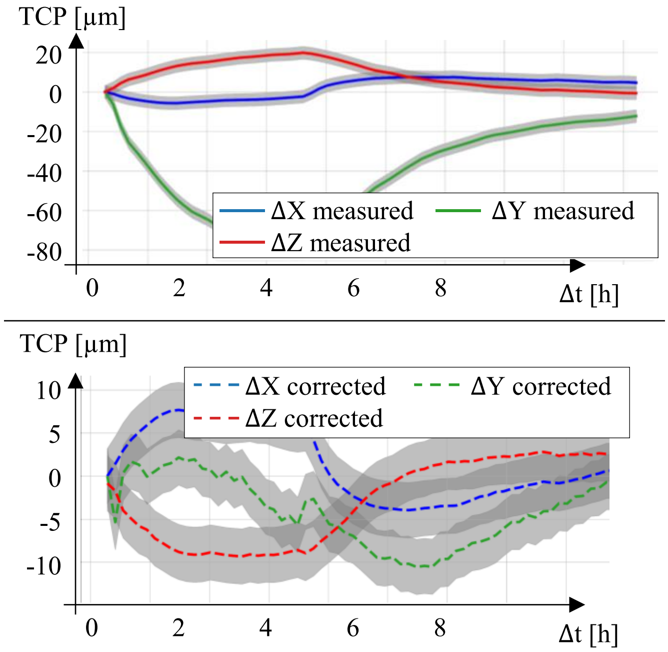

Fig. 6: Remaining error after correction – section 1 – position 1

Fig. 6 shows, that the amplitudes of the TCP-deviation can be decreased significantly; especially the deviation in Y-direction. While the maximum value for the TCP-deviation in Y-direction was measured 75 µm, the correction is able to lower it to a maximum of less than 10 µm. Also, the error in Z-direction is halved. As the error in X-direction was very low even without correction no significant improvement can be seen.

For comparison the Fig. 7 shows the same graphs for the experiment in section 1 but for position 4.

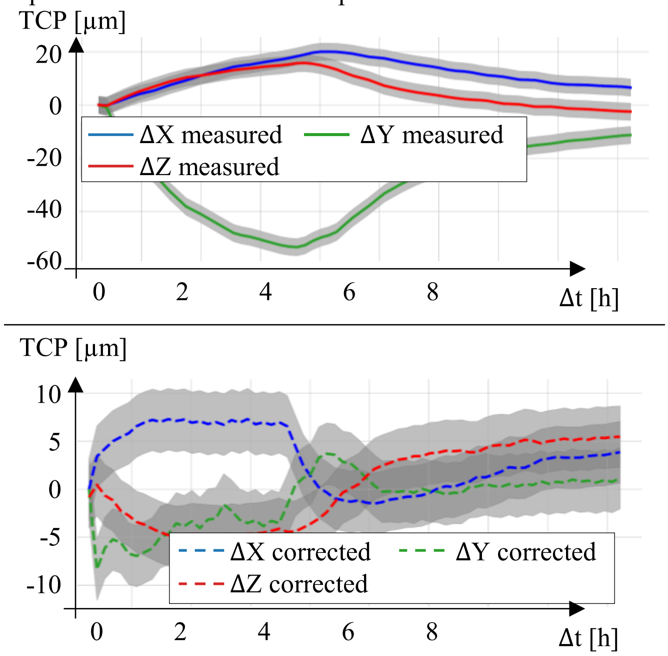

Fig. 7: Remaining error after correction – section 1 – position 4

The result shows once more that the absolute value of the deflection at position 4 is smaller than the deflection at position 1. While it is visible in Fig. 5 that the error between measured

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and predicted TCP-deflection is higher for position 4 than for position 1 over the entire experiment the error is always lower than 10 µm and therefore does not degrade the results of the prediction.

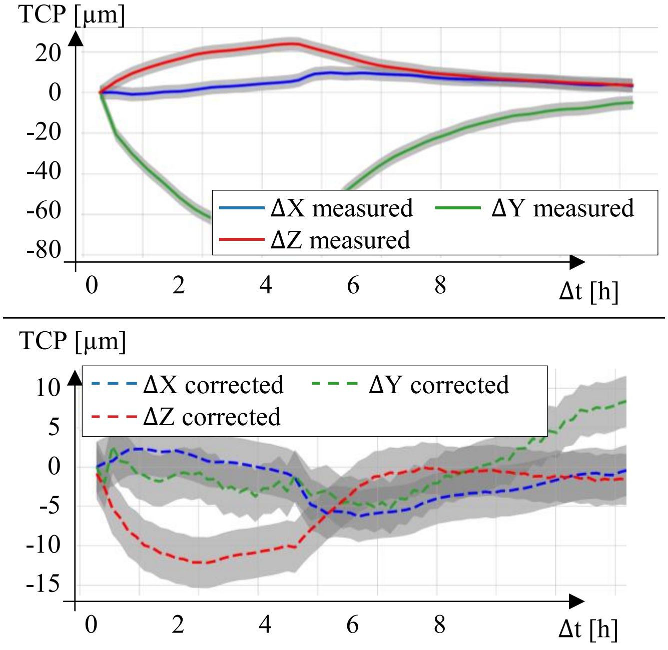

Fig. 8: Remaining error after correction – section 2 – position 1

Fig. 8 shows these graphs for the experiment in section 2 and ball position 1, analogous to Fig. 6. The experiment in section 2 confirms the results from section 1. Here, the remaining errors are smaller than 10 µm for the majority of the experiment duration as well, with a temporary maximum of 12 µm.

4. Conclusions and Outlook

This paper investigated the thermally induced TCP-deflection under load of the machine's axes in two different areas and how precise the presented method can module this error. The question posed can therefore be answered as follows:

- for the same load, the highest amplitude of the TCP displacement at different ball positions varied up to 40 µm in the same spatial direction. The IDS model was capable to predict this displacement with an accuracy of less than 12 µm. Over most of the test period, the difference between prediction and measured TCP is even less than 10 µm.
- for the loads in the different areas, the highest amplitude of the TCP displacement varied up to 25 µm in the same spatial direction. The IDS model predicted these displacements with the remaining errors of 12 µm overall.

The validations therefore show that the prediction based on the IDS measurement can predict the thermo-elastic deviations in all three spatial directions so that an error lower than 12 µm remains.

To validate the model quality in advance, future works will focus on the analysis of the prediction quality

1. for the different loads of Y- and Z-axis in different movement range,
2. for the combined axes movements and
3. for the real milling processes of different workpieces.

Acknowledgements

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