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Online-correction of the thermally induced Tool-Center-Point-deviation based on integrated deformation sensors

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Abstract

It is known, that up to 75 % of geometrical errors are caused by thermally induced TCP (Tool-Center-Point)-deviations. To be able to correct these thermally induced errors a method to measure the thermal deflection of the machines structural parts was developed by Fraunhofer IPT. This method uses Integrated Deformation Sensors (IDS) attached to the machine structure and calculates the TCP-deviation based on a structural machine model. The IDS utilize a rod made out of CFRP (Carbon-Fiber-Reinforced Polymers) as a reference as this material has a significantly lower TEC (Thermal Expansion Coefficient) than commonly used materials in machine tools structural components. The developed model converts the measured structural deformations into the TCP-deviation is based on theories like the Euler-Bernoulli beam theory for one dimensional beams, if the structural part meets the assumptions of a rigid beam, or the Timoshenko beam theory if shear needs to be considered. A similar classification is made for two-dimensional theories. In difference to former publications where the calculated deviation is compared to the measured TCP-deviation in this paper the correction is sent to the machine to reach the goal of an online-correction. To reach this the calculated deflection of the total working area is entered in correction tables which are then transferred to the machine's control to correct the calculated thermally induced error.

The functionality of this method shall be demonstrated in this paper using a demonstrator machine equipped with the sensor-system. For the experiments shown in this paper thermal loads are applied to the machine by moving the machine axes individually while measuring the TCP-deviation using a tactile sensor intermittently. To be able to make statements about the effectiveness of the method said experiment is performed in two variants: one where the correction is disabled to see the uncorrected machine behavior and one where the correction is enabled to see the corrected behavior. The results show that the TCP-deviation is reduced whilst the correction is active.

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

1. Motivation

Thermal issues in machine tools, may their origin be internal or external heat sources or radiaton, lead to a thermally induced deformation of the machines structure which leads to deviations of the TCP (Tool-Center-Point) [1, 2]. The current industry standard is using countermeasures like air-conditioned production halls, warm-up processes or control measurements, all of which are expensive for the producing companies and not sustainable [3]. As an alternative to these measures the IDS (Integrated Deformation Sensors) were developed [4]. While there are multiple methods that have the goal of lowering the TCP-deviation like e.g. [5, 6] most compare their prediction to a TCP-measurement but do not correct this error on the actual demonstrator.

2. Integrated Deformation Sensors

The idea of the IDS is measuring the thermally induced deformation of the machines structure. The sensors can be retrofitted to an existing machine or initially be mounted while the machine is built. A model is used to calculate the TCP-deviation resulting from thermal changes in the machine structure and correct said TCP-error by sending the calculated information to the machine. The methology used shall be explained closer in the following chapters.

2.1. Principle of measurement

The Integrated Deformation Sensor consists of the components schematically shown in ***Figure 1***. To measure the elongation respectively the shortening of the machines structure a rod made of CFRP (Carbon-Fiber-Reinforced Polymers) is used. This rod has, provided that the carbon fibers are arranged in a certain way and the ratio between carbon fiber and the matrix surrounding them are fitting, the characteristic that its TEC (Thermal Expansion Coefficient) is significantly lower than the TEC of materials commonly used in the structure of the structural parts of machine tools, like steel, aluminum or casting materials [4]. While the TEC for CFRP is close to zero or can even be slightly negative the TEC for steel is around $11 \cdot 10^{-6}\,K^{-1}$ depending on which steel is chosen, the TEC for aluminum being even higher at $23 \cdot 10^{-6}\,K^{-1}$. [3]

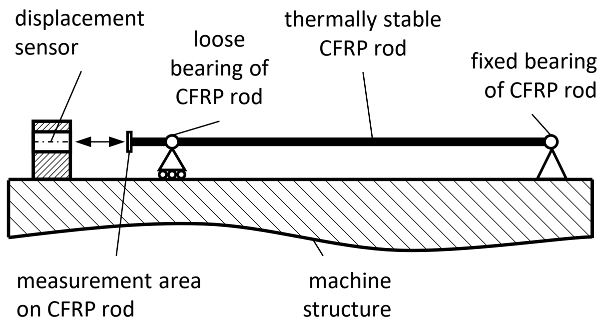

Figure 1. Schematic principle of the IDS

Said CFRP-rod can therefore be used as a reference for the measurement of the structures length-change. The CFRP-rod is, in the example of ***Figure 1***, helt by a fixed bearing on the right hand side and a loose bearing on the left end of the rod. The displacement sensor itself is also connected directly to the machines structure as can be seen on the left hand side of ***Figure 1***. As the displacement that is measured, shown by the arrow in ***Figure 1***, is a superposition of the thermally induced length change and the mechanically induced length change of the structure the measured values need to be filtered. This is in the first place done by a low-pass filter to eliminate elastic length changes that can for example be induced by fast movements of axes or the jerk that can occur e.g. in the moment when a tool is exchanged for another.

2.2 Demonstrator and modeling of the machines deformation

To show the potential of the sensors a demonstrator machine, shown in ***Figure 2***, was equipped with twelve sensors visualized by the dashed lines.

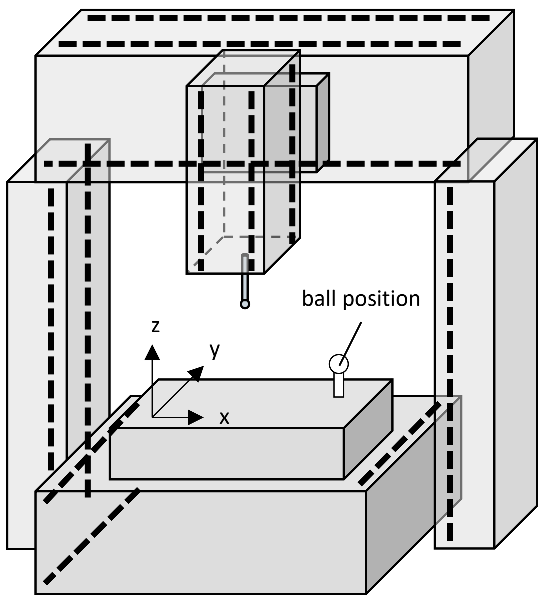

Figure 2. Demonstrator with position of sensors and ball

Five structural parts of the demonstator, a 3-axis machine tool, are fitted with IDS. These include the machine bed, the left and the right column, the portal beam as well as the headstock. The placement of the IDS can be determined either by expert knowledge or with the help of simulations. In these the expected thermal deformations can be estimated by simulating the machines structure together with the sources of thermal energy generated by friction, motors or for example chips that sum up in the process of milling.

To calculate the TCP-deviation from the measured thermal deformation values a model of the machine based on mechanical theories is built. This theory can e.g. be for one-dimensional elements the Euler-Bernoulli beam theory which is used to model beam shaped structural parts where a neglectable amount of shear is expected or the Timoshenko beam theory if the second of these assumptions is not met. In the case of for example the machines bed these dimensional assumptions can not be met, therefore two-dimensional theories are introduced. Similarly to the beam theories the Love-Kirchhoff plate theory is used when there is not a significant amount of shear expected and one dimension of the structure is significantly smaller than the other two. If otherwise there is shear expected the Reissner-Mindlin plate theory is used. These separations are made depending on the shape of all the relevant structural parts of the machine. Whether there is shear to be expected or not is also a part of the simulations done prior. In case of this demonstrator for example the headstock is modelled as an beam because the length in z-direction, according to ***Figure 2***, is significantly larger than the other two spatial directions. The reason this is modelled as an Euler-Bernoulli beam, not a Timoshenko beam, is that from prior simulations where expected heat sources and therefore deformations are simulated there is not a significant amount of shear expected.

This model brings the advantage that no time-intensive data training is needed like in e.g. [7, 8] or also shown in [9, 10]. Instead the model discussed in this paper is based on physical theories used in common mechanics. The deviation of the TCP in the whole working area is then calculated in the form of compensation tables which are iteratively sent to the machine's control which then corrects the TCP by the values in said table. However the point of time for the update of the table is critical as explained in the following section.

2.3 Point of time for the correction

To explain the importance of the point of time in which the correction is updated a simplified example is shown in ***Figure 3***.

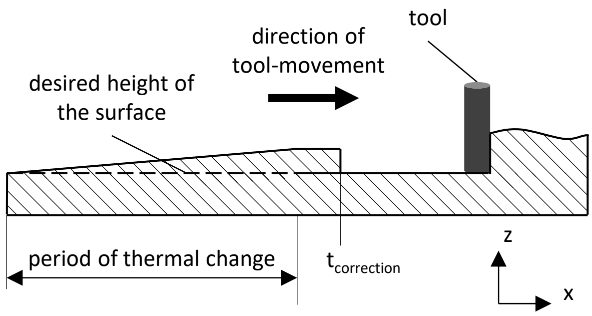

Figure 3. Problem description for the point of time of the correction

In this figure the machining goal would be to machine a planar surface like indicated with the dotted line. However due to thermal influences during the period of thermal change the TCP is deflected in positive z-direction while the tool is progressing in positive x-direction. Therefore the machined surface is deviating from the desired form. If the correction table is updated and the NC (Numerical Control) instantly implements the correction values at the marked place the tool will move in negative z-direction back to the height of the dotted line, creating an undesired edge in the surface of the machined part. It is therefore not only important to model the deviation of the TCP as closely to reality as possible but also to find the right point in time for the update of the correction values.

3. Options for the timing of updating the correction

In this section the possible methods to update the correction table shall be discussed in increasing order of implementation effort and complexity.

The easiest way to implement the iterative update of the correction would be updating it after having passed a certain period of time. Although this brings the risk of manufacturing edges into the workpiece as the the simplification in ***Figure 3*** shows. One way to avoid that would be to interpolate between the old correction values and the updated ones to reach a smoother transition.

Another possibility is to update the table when the tool is not engaged. However, this does not solve the problem shown in ***Figure 3*** for every case. If for example the tool finished one line of the surface and goes on to the next one there would still be a height difference in this simple example. However, this method, as well as the following ones, would need more information than only the IDS measurement either from the machines NC or from an additional sensor system.

Once this communication is established it is also thinkable to update the correction when the machine is changing the tool. This would also solve the problem described above. A similar approach would be to schedule the updating according to work stages like between roughing and finishing. Beneficial for this method is that the roughing usually brings more heat into motors and workpiece as the forces for this step are higher, which would lead to a higher thermal change of the machine.

The technologically most advanced procedure would be implementing lines into the NC-code so that the update of the correction would happen only at advantageous points in time. However this would mean, that while creating said code knowledge of the expected deformation and the correction method would be needed, in contrary to the first method which would be easily automatable completly. This could be feased by an expert who has accumulated knowledge of machine and similar workpieces or for example by implementing an automated method like training an AI-system which aims to predict the optimal moment of time respectively line of NC-code for the update of the table.

Regardless of the point in time when the correction is updated another objective needs to be considered. Usually machine tools already utilize compensation tables, e.g. for slack correction. In this case the machine is calibrated geometrically and based on that measurement a compensation table is calculated which is either constant or updated over long time periods. As there are now multiple compensation tables, it needs to be considered if switching all of these on together, meaning effectively adding them up to the single vector by which the TCP is corrected is the most beneficial possibility or if there are other compensation methods that need to be disabled when using the IDS-based compensation method.

4. Results

To show the functionality of the model experiments under comparable conditions were executed. The demonstrator was switched on but left in idle for the night before the experiments began. Then a warm-up cycle of roughly four hours was performed by continuously moving the x-axis back and forth at top speed to change the thermal state of the machine. The length of the warm-up cycle was set by the number of repetitions of the motions which is why it does not equal four hours exactly but slightly shorter. This warm-up phase was followed by a cool-down phase of 5 hours. As the x-axis was moved it can be expected that especially in y-direction a high change rate of the TCP-deviation will be measured as there is considerable friction from the linear guides and heat coming from the motors going into the portal beam carrying the x-sledge and headstock, leading to a bending motion around the z-axis of the machine. Iteratively every 15 minutes the TCP-deviation was measured tactily over the whole duration of the experiment at four balls mounted to the table, while for reasons of clarity only one ball is shown in this paper, as depicted in ***Figure 2***. The sensor used for this measurement is the Heidenhain TS 649. Due to this procedure the point of time of the update of the correction as discussed in ***Section 2.3*** is not as timecritical as when manufacturing a workpiece. Still for the industrialization of the method the point in time for the update is critical. Therefore the update was done every two minutes which corresponds to the simplest method of updating as described in ***Section 2.3***. In this experiment only one defined position in the working area and only the TCP-displacement of this specific point is considered, relative to the beginning of the experiment. Therfore it is not relevant which compensation tables are in use or deactivated.

To determine the quality of the correction the experiment was performed with the correction deactivated during one execution of the experiment, as a reference measurement, and with the correction activated in three repititions. There were comparable temperature conditions in the shopfloor on all versions of the experiment considered. The following figures show the TCP-displacement in x-, y- and z-direction for the uncorrected case, which corresponds to the reference measurement, and the TCP-displacement for the version of each experiment where the correction was activated over the duration of each measurement.

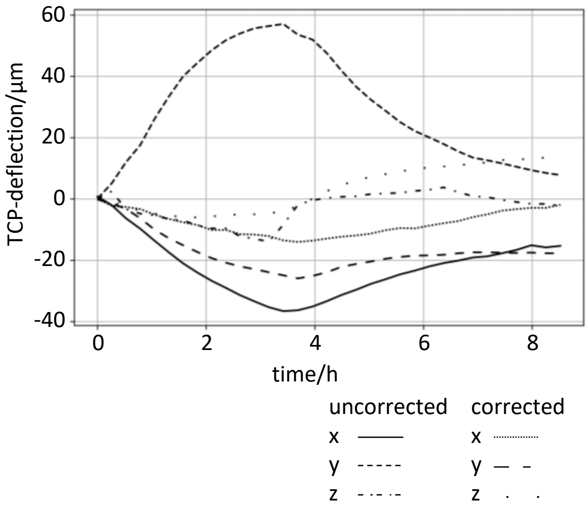

Figure 4. Result of the first experiment conducted

Figure 4 as well as the following show the measured TCP-displacement over the time of the experiments executed while the reference experiment is compared to each one of the three experiments where the correction method was acticated.

The maximum values of the uncorrected case to the x-direction are -37 µm, in y-direction 58 µm and in z-direction 24 µm. With the correction method described in this paper these values are lowered to a maximum of -16 µm in x-direction, 12 µm in y-direction and 7 µm in z-direction.

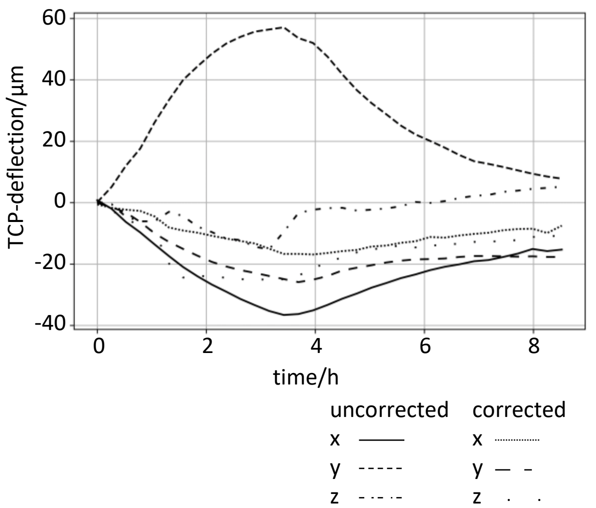

Figure 5. Result of the second experiment conducted

In ***Figure 5*** the results of the second experiment are shown, again compared to the same reference measurement. It is also visible that also while the course of the graph differs compared to the first corrected experiment the maximum value of the corrected TCP-displacement is close to the values mentioned before. It is also visible that while the residual TCP-deviation in z-direction for all three corrected experiments is lower than for the uncorrected case it is not as low as the other two spatial directions, which offers room for improvement of the model.

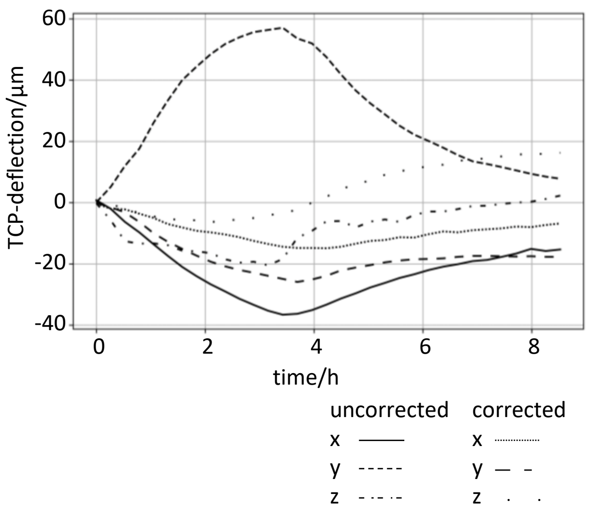

Figure 6. Result of the third experiment conducted

While the corrected and uncorrected values at the end of the experiment have similar values for the TCP-deviation in the z-direction, neglecting positive or negative direction, ***Figure 6*** shows that during all periods of the experiment TCP-deviation is lowered by the correction method.

Figure 4, ***Figure 5*** and ***Figure 6*** show that the corrected and therefore residual TCP-deviation is significantly lowered in every point of time in comparison to the uncorrected case. This is especially the case for the y-direction, as there was the highest displacement of the three spatial directions before the correction due to the bending of the portal beam as described before.

5. Conclusion and outlook

The IDS use a thermally stable CFRP-rod to measure the thermally induced TCP-deviation by measuring the structural length change of the machine. These measurements are calculated into correction tables using mechanical theories for each of the structural parts equipped with the IDS. The correction tables are then sent to the machines numerical control to lower the said TCP-deviation. As shown in ***Section 4*** the IDS-based correction method can lower the thermally induced deviation of the TCP by around 60 % over the course of the shown experiments and therefore improve the thermal stability of machine tools.

In future works the point in time of the update of the correction should be investigated to bypass the potential problems described in ***Section 2.3***. One solution to this would be to implement the point in time for the update of the correction into the NC-code of every part, however this would have the downside that expert knowledge is needed for every new part that is to be manufactured. An alternative to expert knowledge would be the implementation of an automated process that can be based on the known NC-code to find out the ideal point of time respectively line of code to update the table. Additionally it is to be shown if there are already existing correction methods used in machine tools that should not be combined with the method described in this paper, e.g. slack correction. These further experiments could also be conducted using different equipment for the TCP measurement to cover a bigger volume of the working area than in this case four ball positions. Also the influence of machining a workpiece can be considered in further studies, as the heat from this process will also change the machines structural temperature.

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