# Application of Machine Integrated Deformation Sensors

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## Abstract

This paper focuses on a new method for the measurement and correction of positioning errors of the tool centre point (TCP) of machine tools, which can be caused by elastic deformation of the machine structure.

In recent years, the application of deformation sensors in machine structures has been examined in detail. The development of suitable mathematical models utilizing the sensor's signals for actual correction methods has proven to be the key challenge. Results of sensor technology and mathematical model development are presented, showing that major positioning errors of machine tools can effectively be corrected. Furthermore, a sensor system has been applied to machine tools in an actual manufacturing environment, proving high potential for future applications.

## 1 Introduction

The demands for both productivity and precision of metal-cutting machine tools are constantly rising. Further enhancement of productivity is reached by the maximization of cutting performance, which is linearly transferred into thermal output. The resulting variation of the temperature of structural parts causes heat deformation, which is evident in loss of manufacturing precision and errors on the produced work pieces. According to [1] up to 75% of geometrical work piece errors can be traced to thermal issues in machine tools. A higher number of rejected parts and, therefore, loss of productivity is the consequence, if no corrective measures are taken. With recent trends of minimising the energy consumption, applying additional cooling is not a desirable option to minimise thermal deformation. Therefore, new methods of stabilising the thermo-elastic behaviour of structural machine tool parts are required.

It is common in the industrial application, that the thermal elongation or deformation of machine components, such as spindles [2] or tool holders for turning machines [3], is directly measured and compensated. However, these concepts only compensate a fraction of the total tool centre point (TCP) dislocation conditioned by thermal deformation. Still, these approaches have in common, that not only thermo-elastic deformation can be detected, but also deformation due to mechanical loads.

A more comprehensive solution approach, which has been applied in past and present research and development activities is to directly measure the deformation of the machine structure by means of integrated sensors [4], [5], and, therefore, providing a basis for direct or indirect compensation of the deformation [6]. Following the direct measurement approach, this paper describes a particularly robust structure-integrated sensor concept. The basic concept has been developed and tested and is currently being developed further for complex structures of machine tools.

# 2 Solution Approach

## 2.1 Correction Method

The general approach for correction TCP errors due to elastic deformation of the machine's structure is illustrated in Figure 1. In this example, the deformation of the machine column can have a significant influence on the TCP dislocation, especially, if the headstock is in a position near the top of the column. By integrating Sensors in the machine column, its deformation can be directly measured. The measurement is utilised by mathematical model in order to calculate TCP dislocation, regarding the kinematics of the machine, so that axis positions and tool length are taken into account [7].

In the next step, the calculated TCP error is used in order to generate a command for corrective motion of the feed axes of the machine. The TCP now returns to the desired position.

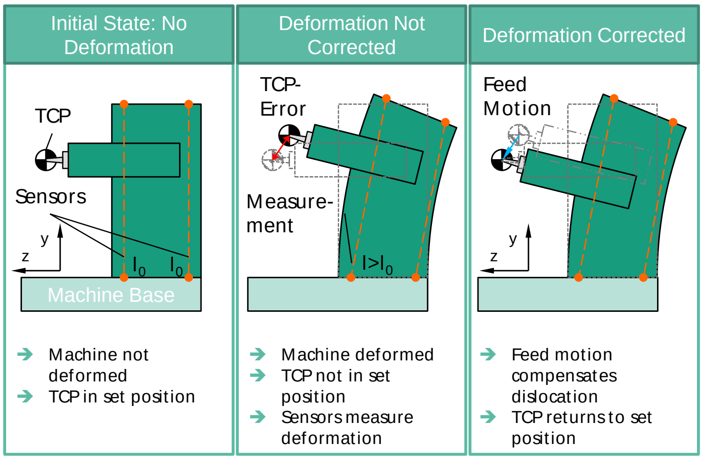


Figure 1: Solution approach

Due to the low complexity of the mathematical model, the calculations can be performed in real-time within the interpolation cycle of the machine controller. Therefore, a process parallel correction of TCP errors is feasible.

## 2.2 Measurement Concept

The measurement concept has been described in detail in [7]. According to Figure 2 it is based on the integration of thermally stable reference rods in the machine structure. In order to ensure thermal stability and low sagging, pultruded carbon fibre reinforced plastics (CFRP) tubes with a thermal expansion coefficient of -0.1 µm/(mK) have been chosen. The rods are installed with a fixed bearing on one side, while on the other side there is a loose bearing, in order to ensure a tension-free rod. The side with the loose bearing is regarded as the free end. With this setup, it is possible to determine the mean elongation of the structure over the length of the reference rod, which is usually in the range of 0,5 m up to over 10 m, by measuring the displacement of the tip relative to a fixed transducer at the free end. This sensor application can be set up at little cost, since most of the functional elements can be obtained as standard parts.

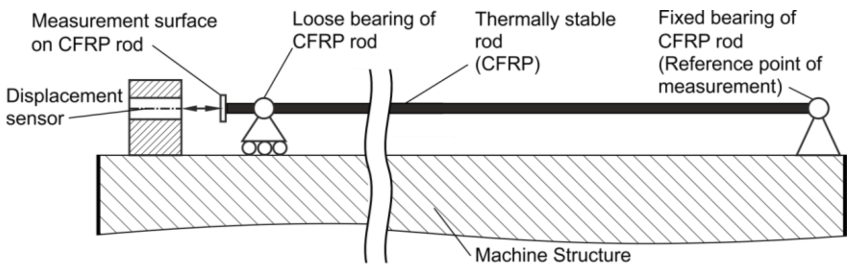


Figure 2: Schematic of measurement principle

For the actual measurement, several transducer types have been tested [7]. The proper sensor should be selected considering the requirements regarding the measuring range and resolution. In the proposed application, a contact linear variable differential transformer (LVDT) gauge has been used (see Table 1 for specifications), which has a rather large measuring range and is thus suitable for the application in large machine tools.

Table 1: Specifications of used LVDT gauge

| Property | Value | Unit |
|---|---|---|
| Measuring Range | 1.25 | mm |
| Resolution | 0.1 | µm |
| Measurement Accuracy | 1.0 | µm |
| Shaft Diameter | 8.0 | mm |

## 2.3 Mathematical Model Concept

The overall model concept has been described in detail in [7]. It is based on the idea, to approximate structural components of the machine tools as cuboid elements, each of which have an integrated sensor system.

In this paper, a model approach for the complex deformation (bending) of the machine column in one plane, see Figure 1, is described. For the model development, the goal has been set to obtain a model, which can be parameterised with only geometric properties of the structural component and the sensor system. In this way, time consuming experiments for obtaining model parameters can be avoided or be kept to a minimum. In [8] it is described that the correlation between the measurements of the integrated sensor and the externally measured deflection of a machine column is highly linear. The linearity has been determined to be ~2 percent, for a load case with uniform bending of the structure. This circumstance endorses the utilisation of a linear model. Furthermore, the model has a minimum complexity and can therefore be calculated within a very short time window.

The geometrical model approach leads to a number of assumptions for the model:

1) The sensor applications are always parallel
2) The distance between the end points of the sensor application on the end surface of the structural component is always the same. At the same time, this means that the distance between the sensor applications normal to the direction of measurement will be reduced, when bending deformation is present.
3) The deformation of a structural component which is covered by an array of sensor applications is regarded to be symmetric.
4) One of the end faces is fixed.

With the above assumptions, it is possible to obtain a measurement of the angle between the end faces α and the deflection of the structure, where $l_i$ are the measured lengths of the integrated sensors and d is their distance in normal direction:

$$\alpha = 2\arcsin\left(\frac{l_2 - l_1}{2d}\right)$$

A similar approach has been defined in [9]. The equation is slightly different, since it is based on different assumptions, namely that the distance between the sensor applications normal to the direction of measurement is constant:

$$\alpha = \arctan\left(\frac{l_2 - l_1}{d}\right)$$

The result regarding its small-angle approximation is the same:

$$\alpha = \left(\frac{l_2 - l_1}{d}\right)$$

In the example of Figure 1, the TCP dislocation due to bending in Z-direction can simply be approximated for small angles as:

$$\Delta z = p_y \cdot \alpha$$

Where $p_y$ is the position of the headstock on the Y-axis, which defines the cantilever for the dislocation due to bending. For other vector components and coordinate directions, similar functions can be set up. For small angles, multiple influences of TCP-dislocation can be superimposed, e.g. when the elongation of the headstock is measured as well.

# 3 Verification and Validation

## 3.1 Error Analysis of Measuring Method

Considering the measurement concept, there may be a number of errors which have an influence on the measurement accuracy. Major error influences are the thermal stability of the etalons, which is mainly affected by the material properties but also by the design of the joints. A major source of error might be the bearing, since in the ideal case a perfect bearing is required in order to avoid bearing friction or a stick-slip-effect compressing or stretching the etalon.

In order to quantify this effect, some experiments regarding the bearing friction have been conducted. A first run of tests has been conducted with very simple, low-cost slide bearings and ball bushings.

Figure 3 illustrates the test setup. The measurement side (free end) of the sensor application is kept unchanged, while the fixed bearing of the CFRP rod is removed and replaced with a loose bearing. In order to detect the effect of the bearings on the measurement accuracy, the displacement of the two tips of the rod is measured and compared. At the fixed side of the sensor application, a micrometre-screw pushes the rod against a spring element.

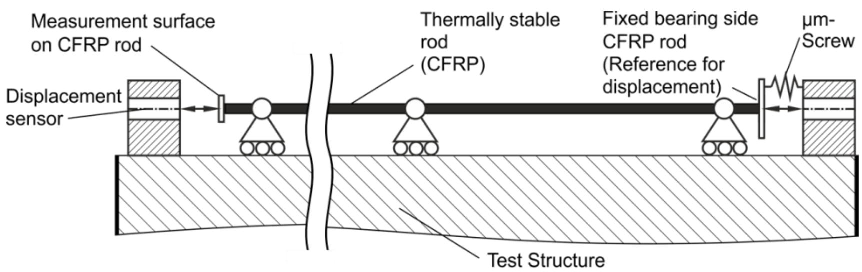


Figure 3: Schematic of test setup for bearing examination

With this setup, a defined displacement of the rod can be set. The experiments were carried out with a reference rod of two metres length with three bearings, where one bearing is located at each end of the rod and one bearing in the middle. The bearings can be exchanged in order to examine the properties of different types. Figure 4 shows a photo and a schematic of the fixed bearing side with micrometre-screw and spring element attached. In this instance, a standard slide bearing is installed.

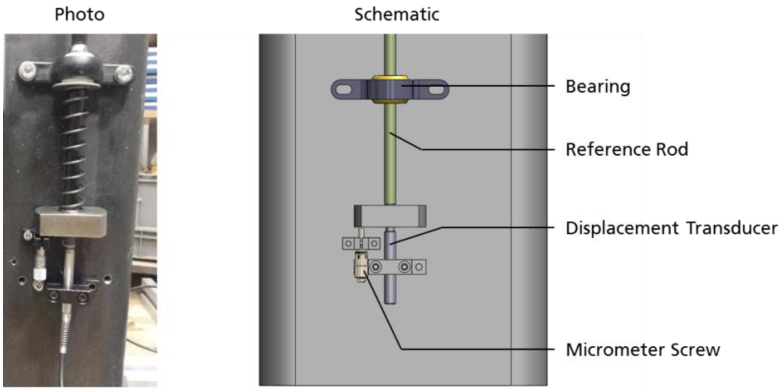


Figure 4: Left – photo of fixed end with micrometre-screw for adjusting the displacement. Right – Schematic of same

For the experiment, the rod was pushed with the micrometre-screw in 5 µm steps within a range of 0.1 mm to 0.2 mm. The test structure was in horizontal orientation, since this is the most critical orientation. In this instance the bearings are loaded with the weight of the etalons, resulting in a higher friction force. Figure 5 shows an exemplary result obtained with standard slide bearings, where the measurements at the fixed side are plotted versus the measurements at the loose side. It is already evident that there are deviations between the measurements, since the measured curve deviate from the ideal straight line.

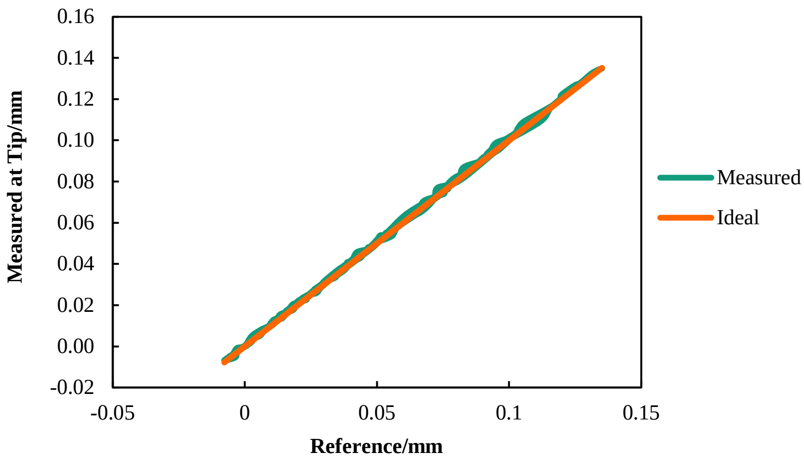


Figure 5: Exemplary plot of displacement of fixed end versus displacement on free end

In order to clarify this, the deviations from the ideal case are plotted in Figure 6 for different bearing types. The respective bar shows the obtained mean deviation, while the error bars show the minimum and maximum measured deviation. The best results have been achieved with simple slide bearings, yielding an average measurement error of 0.6 µm, a standard deviation of 0.99 µm and an absolute error range of ± 3 µm. All values are higher for the ball bushing type. In one bearing setup, an additional angular degree of freedom was implemented. However, the assembly exhibited a severe degree of backlash and produced bad results. It is expected, that the deviations, hence the measurement accuracy, can be improved using e.g. air bearings. However, for the proposed application, the measurement accuracy is considered to be sufficient and the cost of the setup is substantially lower.

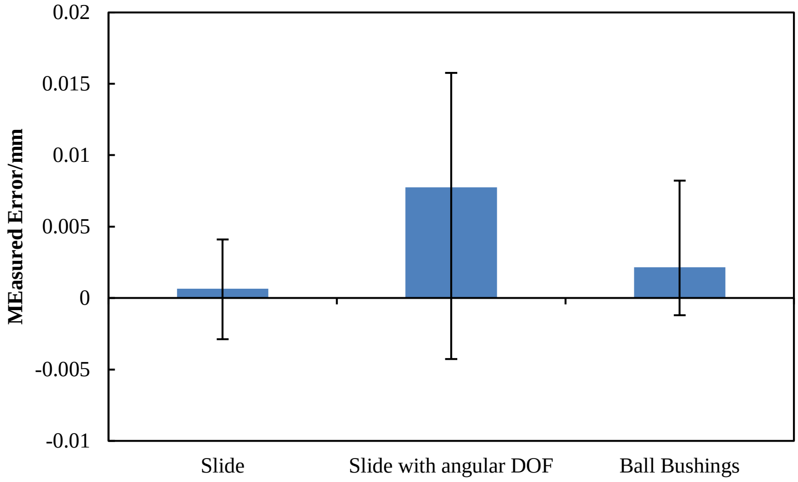


Figure 6: Comparison of measurement error for different bearing types

A sensor system for measuring the elongation of a twenty metres long machine bed has been installed and tested in the field for the duration of over three months with similar results regarding the measurement accuracy [10].

## 3.2 Model Validation Results

The deformation model for a single cuboid element has been validated. For validation a simple test bench, resembling a machine column, has been used. The functional elements of the test bench are described in Figure 7. Made of polymer concrete, the outer dimensions of the test structure are (1 100×390×130) mm³. It is fixed at one side, while the other end can deflect freely due to bending deformation. According to the sensor and model concept, it contains two structurally integrated sensors. Furthermore, it is equipped with heating cartridges in order to be able to induce thermo-elastic deformation. For the purpose of measuring the deflection, an external sensor of eddy current type is located at the free end of the test structure. Furthermore, ten eddy current sensors are evenly spaced on a stable straightedge besides the test structure, so its curvature due to thermo-elastic deformation can be observed in more detail.

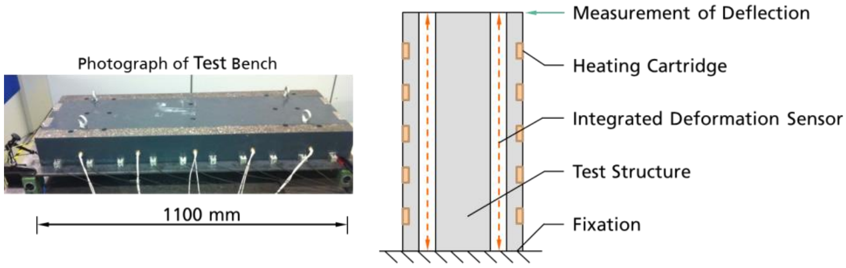


Figure 7: Photograph and schematic of test structure for model validation

The procedure for validation can be described as follows. Initially, all sensor values are set to zero, thus deformation of the test structure is considered to be non-existent. A voltage is applied to the heating cartridges, so the flowing current heats the test structure. This is the designated heating phase of the experiment. The heating is maintained for about thirty minutes until it is switched off. The experiment enters the cooling phase, which lasts for about three hours. All the sensor values, including structurally integrated sensors and external sensors, are recorded once per second for the whole duration of the experiment.

The deflection is recorded directly, while the model generated values for deflection are calculated in post processing. For validation purposes, the measured and calculated deflection values are compared.

Figure 8 shows an example of the results from validation experiments. In this case, asymmetric heating has been applied, namely five of the ten cartridges of one side have been heated. It is expected, that a fairly clean bending of the test structure occurs. The heating and cooling phase of the experiment can be observed clearly. At the end of the cooling phase, the deflection reverts to the initial value. It can also be observed, that only a small maximum relative error of 5.2% between the calculated and measured values occurs. This is in the order of magnitude of the linearity, which has been determined in [8], so the model quality for this load case is considered to be very good.

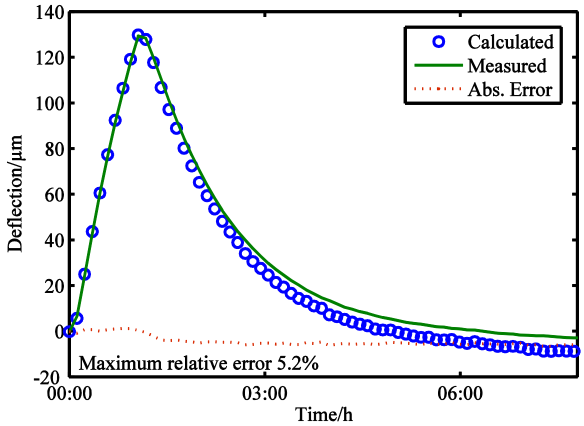


Figure 8: Graph of measured and calculated deflection of the test structures' free end

For the proposed application, this result shows potential for correcting a large percentage of up to 95% of TCP dislocation due to the complex deformation of a machine column.

## 4 Summary and Outlook

In this paper, the application of a sensor and model based concept for the correction of TCP dislocations due to structural deformation has been described.

A low cost measurement setup has been tested and verified under laboratory and field conditions. The detailed examination of the measurement principle shows sufficiently high measurement accuracy for the application in machine tools, even with the utilisation of very inexpensive components. The system can be used in newly designed machine tools, but also be retrofitted to existing machines at very low cost.

Furthermore, a mathematical model has been introduced, which utilises only geometrical parameters of the machine structure and sensor system in order to determine critical TCP dislocations based on the sensors' measurements. This linear model with low complexity can be calculated in real-time, parallel to the machining process. This enables the real-time correction of TCP errors due to structural deformation.

The described systems are currently integrated in a large machine tool and conventional 3 axis gantry type machine tool within several funded projects. In order to be able to utilise the model for more complex structures and deformations, it has been extended with capabilities for linking multiple structural components of the machine. Recently, the developments focus the implementation of correction functions for different NC-controllers.

## 5 Acknowledgements

This work is funded by the DFG (German Research Foundation) within the framework of the trans-regional special research field SFB/TR96 "Thermo-energetic Design of Machine Tools" subproject C03 "Structurally Integrated Sensors" and by the BMBF (German Ministry for Education and Research) within the project "EPSIS – Energy Efficiency and Precision with Structurally Integrated Sensors" under the reference number 02PK2352.

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