In-process measurement of machine structure deformation and compensation of resulting work piece inaccuracies

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Abstract

This paper focuses on solution approaches in order to compensate work piece inaccuracies due to thermal deformation of metal cutting machine tools. A newly developed concept has been verified, which focuses on the direct measurement of thermo-elastic deformations within the structure of machine tools. The solution approach is to measure deformations of machine components directly with multiple specially designed strain sensors. This information can be utilised with a compensation method in order to correct resulting work piece inaccuracies. Compensation can be achieved with the help of a mathematical model, which is used to predict the overall deviation between work piece and tool. The deviation can then be corrected by applying corrective feed axis motion controlled by the machine controller.

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. 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 [5] or tool holders for turning machines [4], is directly measured and compensated. However, these concepts only compensate a fraction of the total tool centre point (TCP) dislocation conditioned by thermal deformation.

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 [1], [3], and, therefore, providing a basis for direct or indirect compensation of the deformation [2]. 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 Principle and Design of Integrated Sensors

According to Fig. 1, the robust measurement principle is based on reference rods, which are integrated in the machine structure. The reference rod is fixed to the structure with a fixed and loose bearing principle. Displacement sensors measure against a measurement surface at the loose bearing tip of the reference rod.

The reference rods are made of carbon fibre reinforced plastic (CFRP) and have a thermal expansion coefficient close to zero. Thus, when the machine structure is elongating, due to thermal or mechanical loads, the sensor is displaced relative to the tip of the reference rod. Therefore, the absolute elongation of the respective region can be measured.

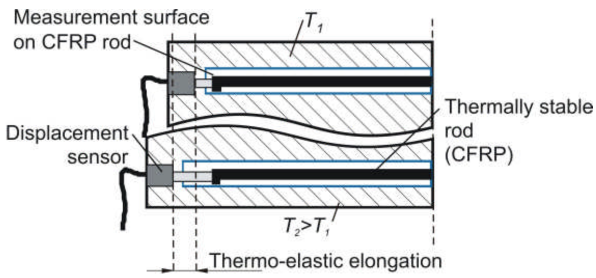


Fig. 1: Measurement Principle with CFRP-rod-based Sensor Concept

A similar concept, based on fibre optical sensors, is shown in Fig. 2. An optical fibre is enclosed and stabilized by a thin CFRP tube. The CFRP tube is mounted with the same bearing principle. Instead of a displacement sensor, a mirror is fixed on the opposite side of the machine structure. The change in distance between mirror and tip of the optical fibre can be measured, based on the interferometric principle.

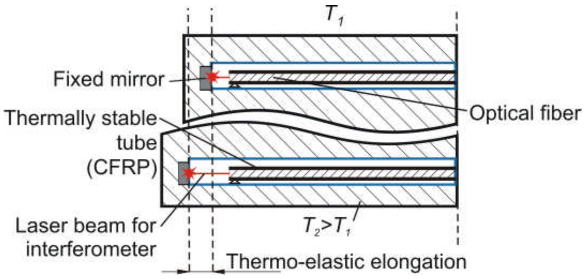


Fig. 2 : Measurement Principle with Fibre-Optical Sensor Concept.

With integration of an array of measurement systems, the determination of more complex deformations is possible. As shown in Fig. 3, an array of two measurement systems allows the identification of elongation and bending in one plane.

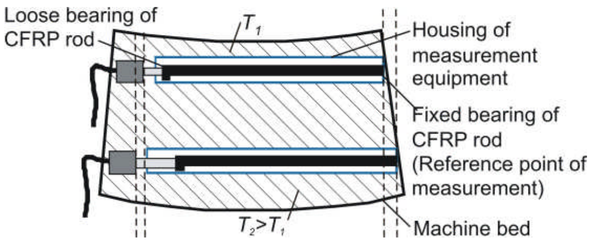


Fig. 3 : Detection of Bending

3 Structural Deformation Correction and Compensation Strategy

An optimised approach for workpiece error compensation in machine tools is the utilization of the internal sensor signals as input values for a mathematical model in order to identify the actual machine deformation. The concept, which is currently being pursued, is the use of a deformation model, which generates data for a kinematic model in order to calculate the axis paths. Herewith, the dislocation of the TCP in regard to the work piece can be determined by direct measurements. The resulting positioning errors can be compensated with corrective NC-axis motion.

3.1 Fundamentals of the Control System Based Compensation Strategy

According to Fig. 4 right, the TCP dislocation δ can be expressed by the difference between the nominal TCP position p and the deflected (by machine structure deformation) TCP position p*.

$$\mathbf{p}^*_{TCP} = \mathbf{p}_{TCP} + \boldsymbol{\delta} \qquad (1)$$

The nominal TCP position on the machine relative to a reference point on the work piece is represented in the machine's control system by a vector chain consisting of the axis measurement system position values a and additional constant lengths c for offset, such as tool length compensation.

$$\mathbf{p}_{TCP} = \sum \mathrm{c}_i + \mathbf{a} \tag{2}$$

This vector chain is depicted in Fig. 4 left between the TCP and the workpiece reference point. It is therefore referred to as outer vector chain. The dislocated TCP position can also be described by a vector chain through the machine base, defined by the internal sensor signals s and constant lengths c, which are considered to be fixed or cannot be measured. Furthermore, the axis positions are considered (a). This vector chain is also depicted in Fig. 4 left inside the machine structure. It is referred to as inner vector chain.

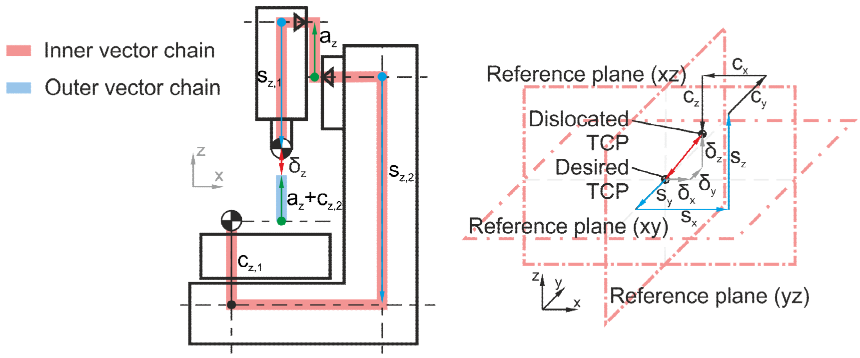


Fig. 4 left: Vector Chain for TCP Position Calculation
right: Description of TCP Dislocation with Internal Measurement System

$$\mathbf{p}^*_{TCP} = \sum \mathbf{s}_i + \sum \mathrm{c}_i + \mathbf{a} \tag{3}$$

The TCP dislocation can be described as the difference between the inner and the outer vector chain. Hence, by applying (2) and (3) to (1), the resulting dislocation vector can be directly expressed with the sensor signals s and constant lengths c, which can be merged. The resulting description of the TCP dislocation is represented in Fig. 4 right.

$$\boldsymbol{\delta} = \sum \mathbf{s}_i - \sum \mathrm{c}_i \tag{4}$$

To calculate the position of the TCP with sufficient precision based on the internal sensor signals, a deformation model based on multiple sensors integrated in the machine structure is required. The sensor and modelling system has to meet the following conditions:

1. The sensor system must be able to represent relevant deformations in every coordinate axis.

2. The deformation of structural components, such as bending, has to be determined in order to consider TCP deflection normal to the sensor axis.
3. The positions of the end points of the sensors have to be known in order to obtain a consistent vector chain. Therefore, suitable reference points or planes are required.

3.1.1 Deformation Model Concept

The concept of the deformation model is depicted in Fig. 5. The machine structure is approximated with a number of connected structural elements. Each element can be described with the information from internal sensors. In the diagram, the machine base of a portal milling machine is approximated with seven cuboid elements. The deformation of a cuboid element (elongation and bending in two planes) can be described with an arrangement of three sensors. Thus, a total number of 21 sensors is required for this type of machine base.

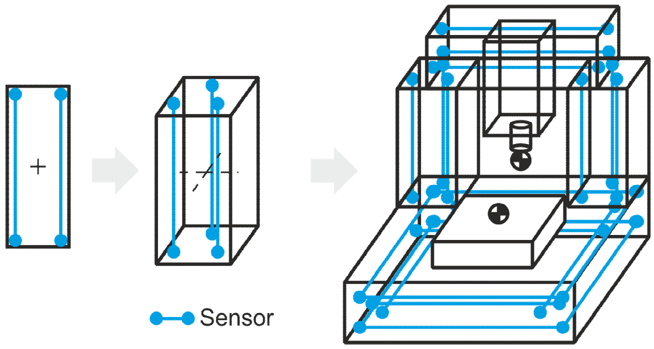


Fig. 5 : Deformation model concept.

For the description of the deformation of a single structural element, different modelling techniques are currently being investigated, namely analytical and statistical models.
Fig. 6 shows a concept of a suitable analytical deformation model for a structural element in two dimensions, which utilizes the internal sensor signals. The internal sensors measure the distance between opposing faces at defined points on the surface. The deflection of a structural element can be calculated, based on the following assumptions.
Depending on the fixation of a structural element, a suitable reference plane may be defined by such a joint between two or more elements. Advantageous reference planes can also be mirror planes of thermo-symmetry or fixed positions on the linear encoders of the axes. The example shown in Fig. 6 makes use of the fixed face on the left side of the structural element.
The second assumption for the analytical model is that the positions of the bearings of each sensor are fixed on each face. In the example this means that the distance d between the sensors is constant. If a high aspect ratio of the sensor

system is chosen, this assumption leads to negligible errors in the resulting deformation calculation.

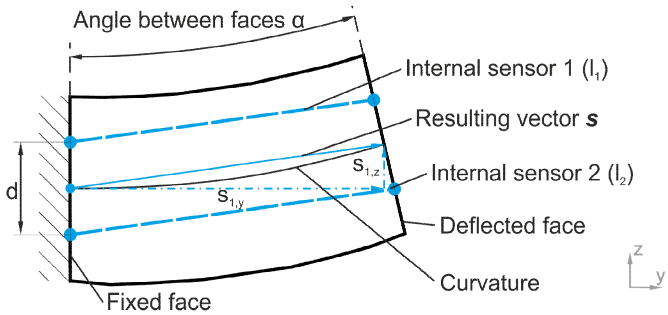


Fig. 6 : Basic Concepts of a Suitable Deformation Model

The resulting deflection is represented by the vector s, which can be used for the vector chain describing the TCP dislocation within the kinematic model.

3.1.2 Kinematic Model Concept

Furthermore, with the information of the internal sensors, the curvature of the structural part can be approximated. The function of the curvature is interchangeable and can either be an analytical function, be based on empirical measurements of test geometries, or be based on FEM simulations.
The determination of the curvature of structural elements is necessary for the description of the TCP dislocation as a function of the axis positions. A clear example would be the Y-axis carriage travelling on a traverse, which is deformed due to thermal load. With the information of the curvature of the traverse and the position of the Y-axis carriage, the deviation of the carriage, and therefore the TCP, to the ideal path can be determined.
With the constant length vectors as additional information, representing fixed lengths of cantilevers, the position of the TCP can be calculated relative to the workpiece.

4 Verification of Sensor System and Compensation Strategies

The sensor concept has been verified on a simple test bench. This section will introduce the test bench and the results of verification experiments.

4.1 Test Stand Design and Setup

In order to verify the above described measurement concepts, a simple test bench has been constructed. The test bench consists of a polymer concrete block comprising two internal measurement systems. The actual displacement sensor type used for the deformation sensor is interchangeable. The suitability of different sensor types for the measurement task can thus be evaluated. For the verification of the internal sensor signals, external capacitive sensors are used for reference. Furthermore, a number of sensor systems based on the fibre-optical system are included. A larger number is possible, due to the smaller size of the setup. The positions of the sensors along the test bench are depicted in Fig. 7.

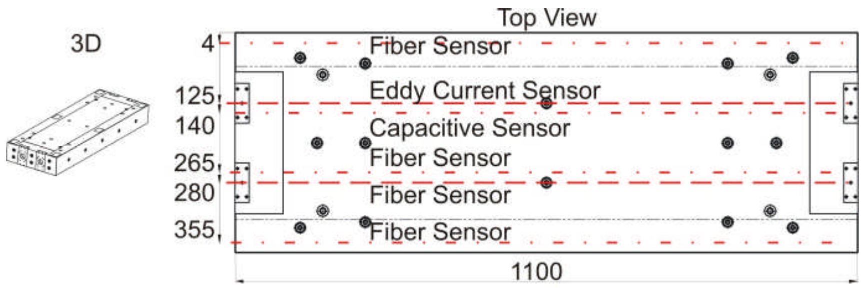


Fig. 7: Placement of Deformation Sensors in the Test Bench

An array of capacitive displacement sensors can be placed on a stable straight edge at the longitudinal side of the test geometry (see Fig. 8). This allows for the measurement of the curvature and deflection of the test bench if bending of the structure is induced. The bearing of the structure is interchangeable, so that both a free floating bearing and fixation of each of the end faces can be achieved.
For temperature control, the test bench contains heating elements and a cooling circuit. The heating elements can be operated independently, so that symmetrical and asymmetrical temperature profiles can be induced in the test bench. Additionally, a total of 42 thermocouples are integrated in a 7x3x2 matrix inside the test bed in order to be able to obtain the temperature field of the structure.

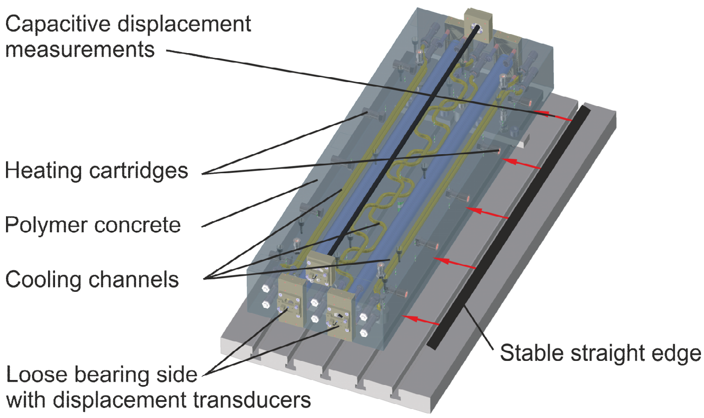


Fig. 8 : Overview of Test Bed Design

4.2 Verification of Sensor Concepts

Different displacement transducer types have been tested on the test bench. Non-contact sensors, such as eddy current, inductive (LVDT) and capacitive sensors have been utilised.
The sensor design with fibre optical sensors described earlier has been tested as well. In summary, all the tested sensor types show sufficient resolution and accuracy for the task.
Fig. 9 shows an excerpt of measurement results of the verification process. It is evident that the signals of the integrated measurement system closely match the signals of the external reference system for both, the LVDT and the eddy current sensor.

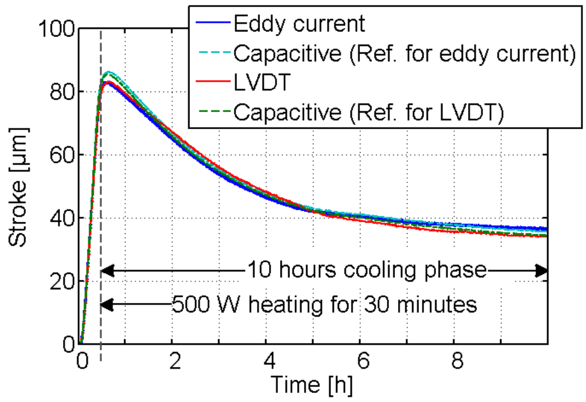


Fig. 9 : Results of Measurement Principle Verification for Elongation

Fig. 10 shows the sensor signals in case of asymmetrical heating (1 hour at 250 W). For this measurement, the fibre sensors have been utilised as well (positions are marked in the plot as depicted in Fig. 7). The sensors show a different signal, depending on their position at the face. This is the result of the bending of the test bench due to the asymmetrical temperature profile. It can be concluded, that bending can be identified and distinguished from simple, symmetrical elongation.

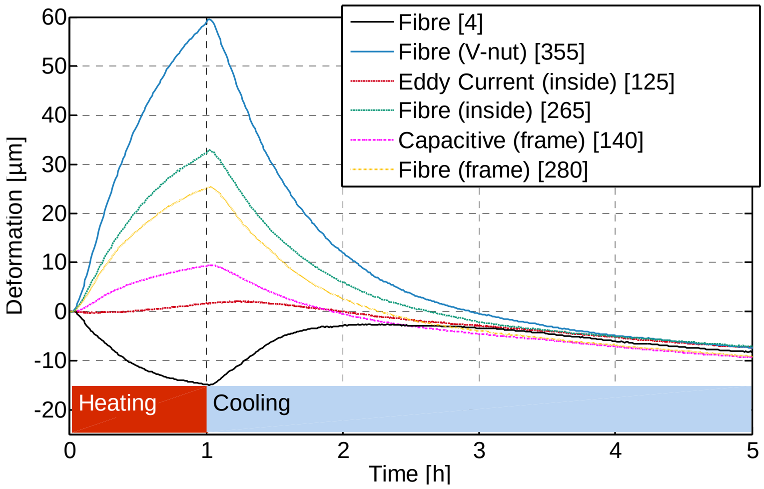
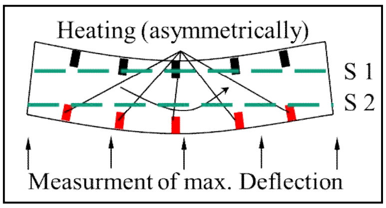


Fig. 10 : Results of Measurement Principle Verification for Bending

In order to quantify the bending of the test bench based on the internal sensor signals, the maximum deflection of the structure has been measured with help of the external sensors. In analogy to the experiments shown in Fig. 10, asymmetric heating has been applied to the test bench, so a bending deformation has been induced.

In Fig. 11, the maximum deflection of the test bench has been plotted versus the internal sensor signals. The result is a trace which indicates the relation between the parameters. It is obvious, that the maximum deflection of the structure can be approximated with sufficient accuracy by the internal sensors, since the measured values are in the same order of magnitude. Further experiments will focus on different qualities of deformation and repeatability.



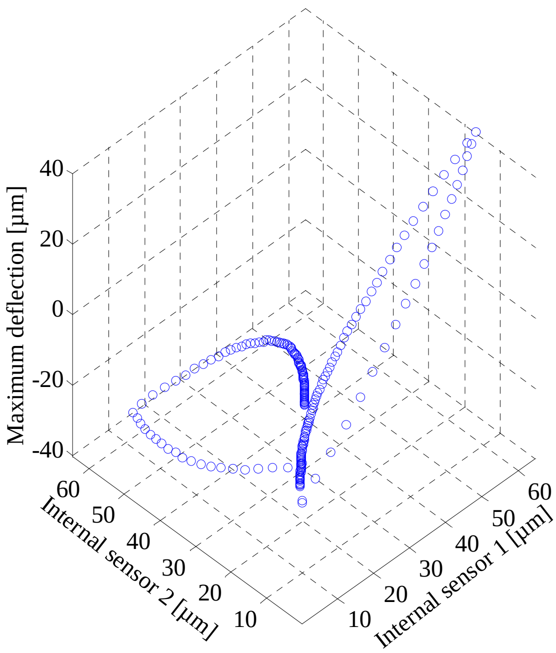


Fig. 11 : Maximum deflection of test bench over internal sensor signals

4.3 Verification of Control System Based Deformation Compensation Strategy

In order to verify the control system based deformation compensation approach, a sensor and compensation system is being developed using the example of a three axis portal milling machine. The polymer concrete machine bed of this machine will be equipped with a comprehensive sensor system of 21 sensors with an arrangement similar to the one depicted in Fig. 4.

In analogy to the verification test bench, the test machine contains heating elements in order to simulate different thermo-elastic loads. Hence, different temperature profiles can be induced in the machine bed. The test machine, furthermore, will have three NC axes controlled by a standard control system in order to verify the axis feed compensation strategy. In order to deliver TCP dislocation data constantly, the deformation model will be implemented in the control system. The NC system is able to use this data for correction via the axes. In the end, the effectivity of the developed mathematical models and compensation strategies can be evaluated with external measurement equipment.

5 Summary and Outlook

In a first verification process different measurement applications and sensors for the direct measurement of deformation have been tested. For this, a simple machine bed geometry, made of polymer concrete, with integrated sensor and

heating devices has been built. Different thermo-elastic states like elongation and bending of the bed have been induced. Within test measurements the concept has been verified and the capabilities of different sensors have been evaluated.
Presently a NC controller based compensation strategy will be investigated in a special research field. The fundamental concepts for this approach have been introduced. Results of validation experiments for the utilisation of the integrated sensor system for predicting the machine deformation have been shown. The introduced deformation model is currently being implemented. It will be applied for and verified with the polymer concrete block test stand for different types of fixtures and reference planes. Furthermore, the application of the compensation strategy will be developed further by integrating it in a real machine system.

6 Acknowledgements

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