Laser-based measurement of thermo-elastic structural deviation of machine tools

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Abstract

Thermo-elastic deformations are one of the most significant sources of machine tool inaccuracies. The structure components of the machine tools can elongate and also bend due to inhomogeneous distribution of temperature in the machine structures. There are numerous methods to measure and monitor structural deformations. However, the measurement of the structural bending is still very challenging procedure.

In this paper, a simple laser-based sensor is introduced for the measurement of the structural bending of machine tool components. The sensor is made of a laser unit, a precision optics based on charge-coupled device (CCD) and electronics for image processing. These measuring hardware are mounted in a metal tube: the laser at one end of the tube and the CCD at the other end of the tube. With the change of the laser beam position on the CCD, the bending of the tube can be measured perpendicular to the laser line of sight in two dimensions. To measure the accurate laser position, an image processing algorithm is applied and embedded in the integrated electronics.

For the validation of the sensor capability, the sensor is mounted on two different machine tools. The measurement of the sensor is applied under thermal loads of axis movements after ISO 230-3. The sensor potential is analyzed with the correlation between the sensor measurement and different independent validation measurements.

1 Introduction

Thermal behavior of a machine tool has a significant influence on the machining accuracy. Recent research shows that up to 75 percent of workpiece errors are induced by thermal errors of machine tools [1]. In order to achieve a higher cutting performance, an optimization of the temperature behavior is necessary. An effective and cost-effective optimization approach is the indirect correction of thermal errors. In this approach, a mathematical model is required, which can estimate the current thermal displacement by means of the machine state variables.

A common and economical state variable is temperature. This approach is widely used in industry and research. Rarely, deformation is used as other state variables. However, the deformation measurement gives a high correction potential of thermo-elastic errors. The reason for this is a relatively low complexity of the relationship between structural deformation and displacement of the tool center point (TCP).

This paper presents a novel sensor which can measure the deformation of the structural bending easily based on laser and CCD sensor. The sensor is developed for simple applications on different machine tools in the future. For the validation of the sensor potential, the sensor is investigated on two different machine tools.

After reviewing the previous work in the literature in Chapter 2, the measurement principle of the sensor and its development is introduced in Chapter 3. For the validation of the sensor, the measurement setup and result of the experimental investigations is described in Chapter 4. Finally, the conclusions and the outlook for future research are summarized in Chapter 5.

2 State of the art

The measurement methods of structural deformation can be divided into punctual and integral measurement. In punctual measurement, the strain at a certain point of the structure is to be measured. Strain gauges [2] or sensors with fiber Bragg gratings (FBG) [3] can be used for the punctual measurement. In integral measurement, the mean strain along a particular line of the structure is to be measured. For this purpose, the relative displacement of two points, mostly in one dimension, is measured. This chapter gives a review of the integral measurement methods of structural deformation.

One measurement principle of the integral deformation is using expansion rods which is firmly clamped at both ends. The rod is advantageously made of a material such as Invar which has a significantly lower thermal expansion coefficient than the structure to be measured. The sensor for the punctual strain measurement is applied on a certain position of the rod. Since the tensile or compressive stress along the rod is constant, the measured strain is proportional to the relative displacement of the rod. This principal method is described in the work of Wulfsberg, Hatamura and Bosetti [2, 4, 5].

Another measurement principle of the integral deformation measurement is using a reference rod. This is developed by Brecher et al. [6]. Here, in contrast to the method of the expansion rod, just one end of the rod is clamped. Therefore, the rod has no internal stresses and is used as a reference length. The rod is made of carbon-fiber-reinforced plastic, which also ensures a very low thermal expansion coefficient. The relative displacement can be measured as the structural deformation at the loose end of the rod with a displacement sensor. The advantage of this method over the expansion rod is that the measurement method does not require the calibration of the rod. Laser can be also applied with the interferometry principle instead of a rod and a displacement sensor [7-9]. Liu [3] applied later a similar measurement, however based on Fiber Bragg Grating sensors instead of rods.

If other dimensional deformation such as bending are to be measured, several above mentioned deformation sensors are required. Depending on the requirements, the sensors can be applied in different orientation. Verdi applied the sensors parallel and crossed orientation to measure the bending, shear and torsion of the machine bed [7]. Bosetti applied the punctual deformation sensors in a net-like orientation on machine structures to measure the multi-dimensional deformation [5].

Another simple method to measure the lateral deviation is using the laser and position sensitive device (PSD) or CCD-Sensor [10]. However, the laser beam can be strongly influenced by the environmental condition such as temperature gradient, dust or chips. Thus, this is very crucial for the application in machine tools. This paper presents a laser and CCD based sensor system which is isolated from the environment and, therefore, stable against the machine tool environmental condition.

3 Sensor development

The bending sensor comprise a laser module with a high precision optical system forming a tiny laser beam at a distance and a camera module analyzing the position of the laser beam. This position depends on the deformation of an encompassing housing, i.e. an aluminum tube (Figure 1).

Figure 1 Sensor housing

An important principle of the optical design is the laser beam projecting directly on the camera chip CCD without any object lens (Figure 2 right). Therefore the size of the laser beam has to be in sub-millimeter range and the illumination power has to be weak enough not to overexpose the camera and strong enough to ensure laser (and not just led-) operation. The center point of a laser point projection is calculated und tracked over time on the camera module locally (Figure 3 left).

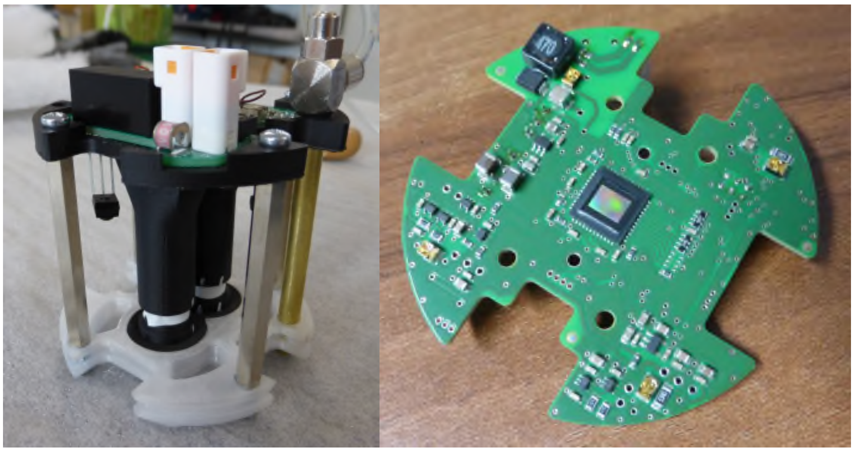

Figure 2 Laser module with two optical systems (left). Camera module with open CCD (right)

More tubes can be (mechanically) concatenated to capture longer and more complex shapes. They are linked as a daisy chain system. Up to 4 chains (with maximum 127 sensors each) can be attached to a control unit (Figure 3 right). The control unit ensures correct power conditions, monitors sensor health and coordinates communication from the sensor chains to external computers.

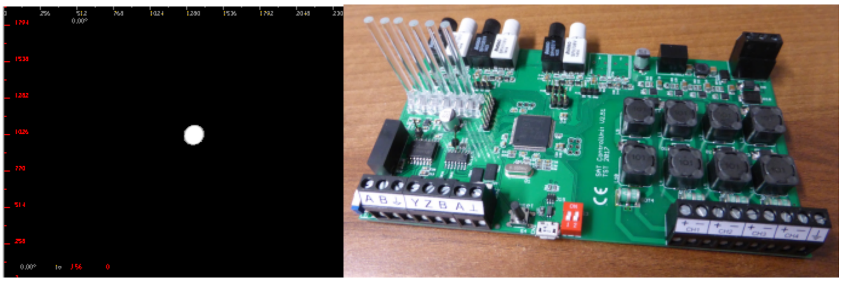

Figure 3 Camera Pattern (left) and Sensor Control Unit (right)

A sensor tube is ruggedized mechanically, optically and electrically. To prevent mechanical damage to the modules, they are casted at both ends with an adhesive based on epoxy resin. The resin also guarantees the precise arrangement of the optical system and therefore the laser beam arrangement relative to the housing tube. The castings are finalized with opaque layers at the top to ensure darkness in the measurement compartment (Figure 4). The tube is filled by a special gas to ensure optical quality and prevent mist on the optical components.

A number of electronic protection systems are realized for this sensor. They are important, because the sensor system is also designed for the observation of large objects up to several hundred meters long. By this extend, lightning strikes and other EMC and ESD issues occur. Therefore, only the power line is connected to the sensor tubes by copper cables. For communication, the tubes are connected by optical fibers and the camera module communicates with the laser module by infrared light in the measurement compartment. The power lines are protected by surge diverters and protective diodes on the control unit and on each module. The PCB layout is for EMC optimized.

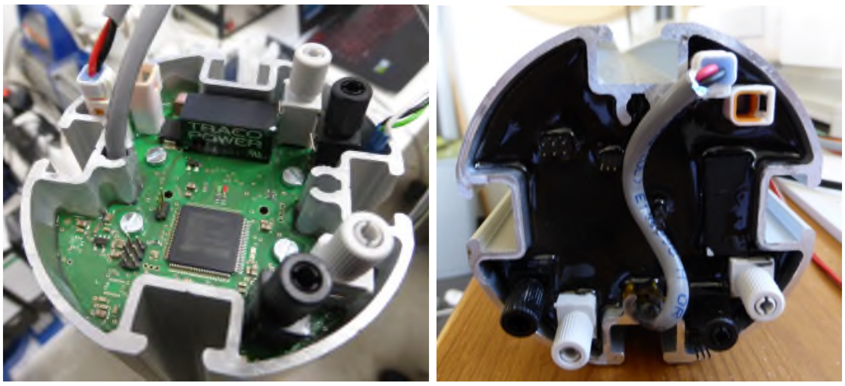

Figure 4 Casting of modules in the aluminum housing tube

A big advantage of this measurement principle is, the usage of the CCD pixel metric, which is given with high accuracy in sub-micrometer range for length and orthogonality measurement (in contrast to photo sensitive elements (PSD) where nonlinearities have to be tackled). This yields a subpixel measurement uncertainty of 0.44 µm and a measurement range of 5.3 x 3.8mm. The frame rate for a sensor (chain) is about 100 Hz.

4 Experimental validation

For the experimental validation, two TST sensors with different lengths are developed and applied at two machine tools. First, a TST sensor with the length of 1 m is mounted in Z-direction along the column of a three axis compact machining center as in Figure 5. The machine tool has an integral deformation sensor (IDS) mounted in the portal beam. This IDS is made of a CFRP rod and a measurement probe as described in [11]. Since the applied CFRP rod has very small thermal deformation, this IDS in the portal beam of the machine tool measures the thermo-elastic expansion of the portal beam in X-direction. The performance and the measurement uncertainty of the IDS is analyzed in further in [11]. Thus, the IDS is applied as an independent measurement method for the validation of the TST sensor in X-direction.

The measurement of the TST sensor is applied continuously with 50 Hz under thermal loads of X-axis movements according to ISO 230-3 [12], since the applied machine tool suffers from high thermo-elastic deformation of the portal beam during X-axis movements. The X-axis was moved repeatedly at rapid feed rate of 80 m/min for the full available travel distance. After a heating phase of 4 hours, the measurement continued during cool-down for additional 5 hours. During the experiment, the thermo-elastic deformation of the portal beam is measured continuously with the IDS in X-direction. Since the machine tool has a thermo-symmetrical design in X-direction, the TST sensor should measure in X-direction the half of the IDS measurement value, assuming the thermo-elastic deformations of the machine bed bottom structure are relatively very small.

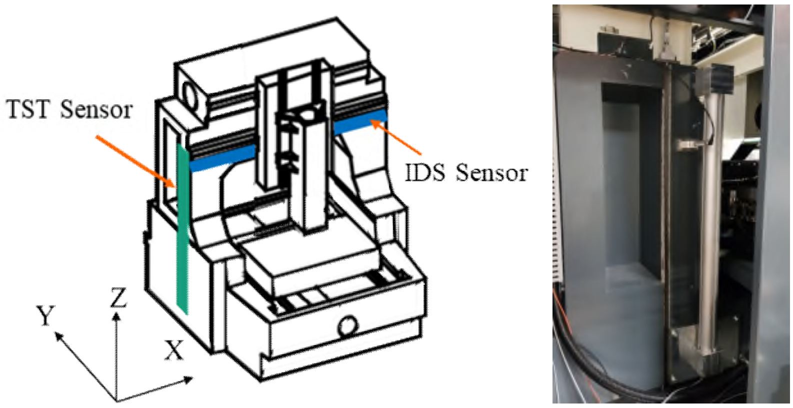

Figure 5 Applied three-axis machine tool with installed TST and IDS sensor (left), TST sensor installation at the Z-column (right)

Figure 6 shows the measurement results of the IDS and TST sensor. The measurement values decreases with heating and increases with cool down. The TST sensor in X-direction shows high correlation to the IDS measurement in the heating phase. Although the relative behavior between IDS and TST sensor is slightly different over time, the maximum value of the TST sensor measurement (app. 60 µm) is almost half of the according IDS measurement (app. 120 µm). In the cool down phase, the TST sensor value changes relatively stronger than IDS. This could be influenced by the measurement uncertainty of the TST sensor and the different structural cool down velocity due to their unsymmetrical cover design around the machine bed. In Y-direction the column bends in negative direction with heating and shrink back with cool down.

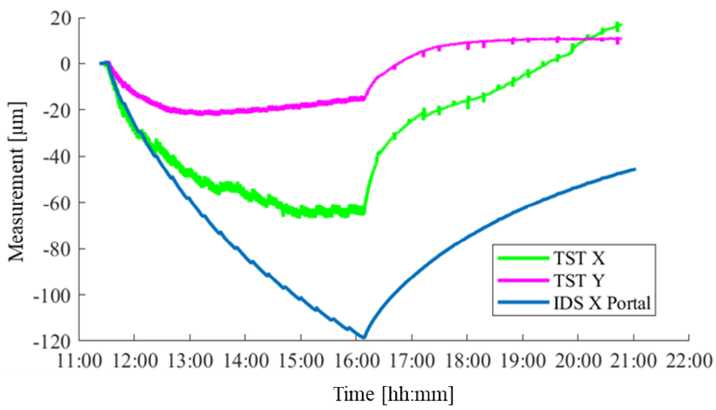

Figure 6 Measurement result of TST and IDS sensor

For the further experiment, a second TST sensor is applied at the bottom of the Z-slide of a traveling column milling machine as in Figure 7. The machine has limited accessibility to mount the TST sensor over the full length of Z-slide. Thus, the second sensor is developed with a length of 1.8 m and measures front part of the Z-slide. As independent validation measurements, two dial gauges are mounted near to the TCP and measure the thermo-elastic deformation directly on a granite straight edge each in X- and Y-direction. Since the machine suffers from high thermo-elastic deformation of Z-slide caused by Z-axis movements, the experiment is applied under thermal loads of Z-axis movements similar as above experiment. The Z-axis was moved repeatedly with its maximum speed for the full available travel distance. After every 60 back and forth movement cycles, the TST sensor and dial gauge measurement are applied at several Z-axis position. At the cool down, the measurements are applied after every hour.

Figure 7 TST sensor integration at Z-slide of a traveling column milling machine (left) and measurement setup of dial gauges and straight edge

The measurement result in X-direction is shown in Figure 8 and Figure 9. First measurement set at the beginning of the experiment is taken as a reference state and subtracted from all following measurements. Since the Z-slide bends in negative X-direction under the Z-axis loads, the measurement values of the dial gauge increase with the Z-axis position. The slope of the measurements increases during the heating and decrease back to almost the reference state after three hours of cool down.

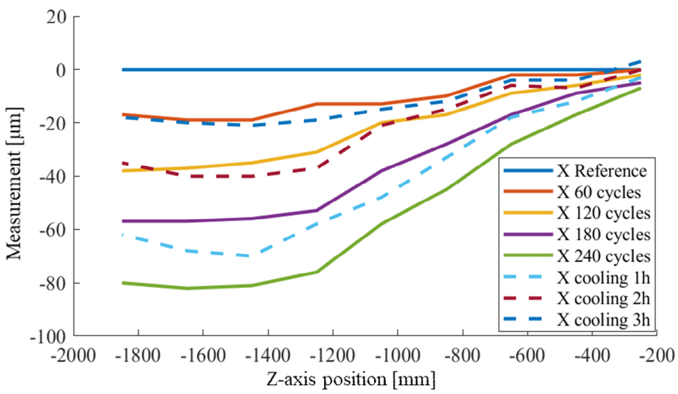

Figure 8 Measurement result of dial gauge (X-direction)

The TST sensor measures the relative deformation between two sensor ends. Thus, the measurement value can be interpreted as a slope over the sensor length and does not variate much over the Z-axis position (Figure 9). The TCP deformation can be calculated based on the TST sensor measurement and Z-axis position as in Figure 10. The calculated deformation follows the trend of the actual deformation in Figure 8 very well. Approximately 50 percent of the actual deformation overall could be described with the applied TST sensor. The remaining deformation is probably due to the sensor measurement uncertainty and short sensor length relatively to the Z-slide.

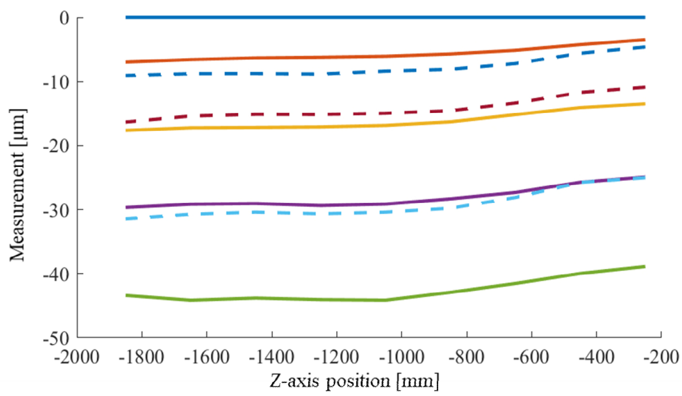

Figure 9 Measurement result of TST sensor (X-direction)

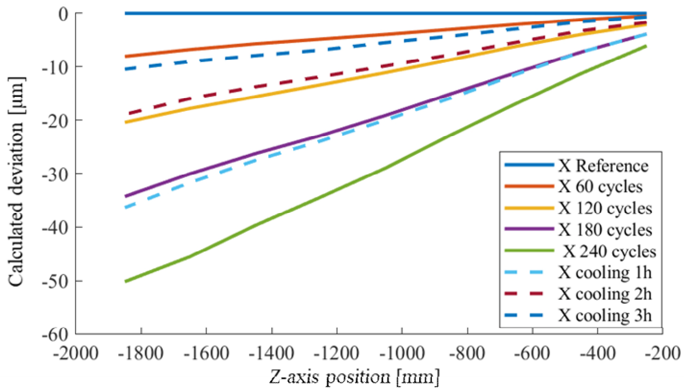

Figure 10 Calculated TCP deviation based on TST sensor measurement (X-direction)

The measurement of the TST sensor in Y-direction did not show robust result. Since the sensor housing is aluminum and the machine structure steel, the thermal expansion coefficients are different. Thus, the ambient temperature variation causes the sensor deformation which probably influences in Y-direction due to the weak one-sided mounting situation of the sensor. The sensor is initially developed for the four-sided mounting in the target machine structure, which was not directly possible at the applied machine.

5 Conclusion and outlook

In this paper, a novel sensor (TST sensor) is presented which can measure the lateral deformation of the structure. The TST sensor applies laser beam and CCD without any object lens. Since the environmental condition affects the laser beam strongly, the laser and the CCD are attached in an aluminum tube and measure its deformation. Using an image processing algorithm, the position of the laser point on the CCD is calculated locally in the sensor system.

For the first validation experiment, the developed TST sensor is mounted at the left column of a compact three axes machining center to measure its structural bending. The measurement is applied under thermal loads of X-axis movements and cool-down after ISO 230-3. During the experiment, the structural expansion of the portal beam in X-direction is measured with an integral deformation sensor (IDS) which is mounted in the portal beam. The measurement results show that the TST sensor measurement in X-direction follows the trend of IDS measurement very well.

For the second validation experiment, the TST sensor is mounted on a traveling column milling machine at the bottom of the Z-slide. During the heating with Z-axis movements and cool down, the TCP deviation is measured periodically with the dial gauges and straight edge. The TCP deviation is calculated based on the TST sensor measurement and Z-axis position. In X-direction, app. 50 percent of the actual TCP deviation could be modelled with the TST sensor, even the sensor length and location is not optimal. In Y-direction, the measurement did not show robust results, which is probably due to the error-prone mounting method of the sensor on the machine structure.

The future research should focus on two subjects: 1. Further analysis and development of the sensor, 2. Application of the sensors on the multiple structures of the machine tools. The measurement uncertainty of the sensor is calculated based on the CCD pixel and laser beam size in this paper. This has to be validated also with an experimental analysis for self-heating of the system and effects of heat conducted through the machine structure on measurement uncertainty. Since the sensor housing is aluminum and the machine structure generally steel, the ambient temperature variation can cause the sensor deformation as an additional uncertainty. This can be solved with better mounting of the sensor in the machine structure or a new design of the sensor housing. The thermo-elastic deviation are generally caused by deformation of multiple structures of the machine tool. Thus, several sensors will be applied each in different major structures. Finally, the TCP dislocation can be modelled mathematically and compensated afterwards based on the measurement values of the sensors.

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