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Laser triangulation-based thermal characterization of machine tool spindles according to ISO 230-3

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Abstract

To characterize the spindle displacement of a machine tool over time due to the heat generated by the spindle motor during operation, a measurement setup was developed consisting of five laser triangulation sensors arranged according to ISO 230-3. It is based on a modular, lightweight frame with features for quick disassembly for easier transportation and re-assembly with high repositioning accuracy enabling to run the test at different locations on different machines. To localize the laser spot on a rotating tungsten carbide bar, an on-machine laser beam origin and direction detection strategy for laser triangulation sensors was developed. The position of the bar was mapped in the three-dimensional space by a best-fit algorithm. The characterization of the thermal deformation of a machine tool at 15000 rpm over 1.7 hours showed robustness to the underlying laser origin and direction measurements and was demonstrated as suitable tool to analyze machine tool's thermal compensation strategies. The most influential error contributors were identified and discussed.

Machine, Measuring instrument, Precision, Thermal error

1. Introduction

To ensure the performance of machine tools and thus the quality of machined parts, the ISO 230 series of standards covers methods and tests for evaluating machine characteristics. ISO 230-3 [1] describes displacement sensor-based tests for characterization of thermal distortions and drifts from rotating spindles. Commercial spindle error analysis systems typically consist of either three or five capacitive displacement sensors, placed in a fixture and measuring on a rotating artifact mounted on the spindle [2,3]. The displacement of the spindle with respect to the machine table in X-, Y-, and Z-direction can be characterized with three sensors, the tilt error movements in the XZ-, and YZ-plane can be characterized with one additional sensor each in the X- and Y-direction at known distances.

A versatile test setup to characterize machine tools according to ISO 230-3 consisting of five laser triangulation sensors (LTS) on a compact modular frame allowing for easy handling and assembly with high repositioning accuracy was developed. LTSs have been selected because they are insensitive to the shape and material of the target and are suitable for high-resolution non-contact measurements at high rotational speeds of the measured object at sampling rates up to 50 kHz and are less expensive compared to other high performance measurement technologies.

2. Methodology

2.1. Laser triangulation sensor

LTS are typically used for displacement, position, thickness, or dimensional measurements as they offer high resolution down to 30 nm, high linearity of 600 nm, a small beam spot size, long measuring ranges, high reference distance between sensor and target reducing the risk of damage during setup, and independence on the target material [4]. However, the relatively large sensor compared to confocal, capacitive or eddy current sensors makes the setup bulkier and a relatively clean optical path is required for reliable operation.

The distance measuring technique is based angle calculation and illustrated in Figure 1. A laser beam is projected onto the object to be measured. The distance to the object is determined using the known distance from the transmitter to the receiving element and the angle of reflection of the laser beam on the receiving element. Its components are assembled in an aluminum casing, among which the laser diode and processing unit are potential heat sources. The thermal behavior of the LTSs used was investigated. The results are presented in Section 3.

Five LTSs type optoNCDT ILD-2300-2 from Micro-Epsilon with 670 nm wavelength, mid of measuring range (MMR) at 25 mm, 2 mm measurement rage, 30 nm resolution and a maximum sampling rate of 49 kHz were used [4], operated in diffuse mode without any filter nor averaging.

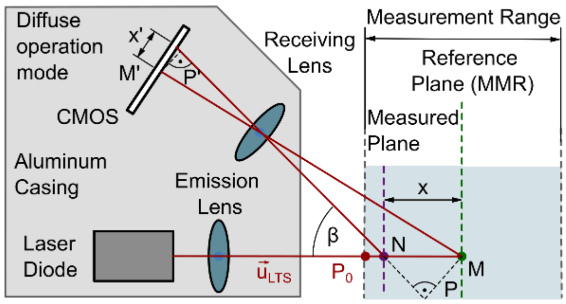

Figure 1. Laser triangulation principle in diffuse mode.

2.2. Modular frame

A modular, lightweight frame concept shown in Figure 2 was developed and additively manufactured from tool steel. Each sensor is permanently fixed in its own bracket with machined reference surfaces allowing for further use of the sensors in other measurement setups without losing their positions within the brackets. Three ceramic spheres per measurement direction are fixed on the frame. The brackets are attached to the frame with magnets that align with the ceramic spheres allowing the sensors to be quickly assembled and repositioned with high accuracy to perform the test in different locations.

Three parallel groves perpendicular to the measuring direction with 5 mm spacing on the brackets enable measurements on bars with diameters of 10, 20, and 30 mm in diffuse mode, as shown in Figure 2. A second set of groves rotated by 10.25° on the bracket and six additional spheres on the frame allow to operate the LTS pairs in X- and Y-direction alternatively in direct reflection mode. The position of the LTS in the Z-direction is fixed and therefore only suitable for diffuse measurement mode.

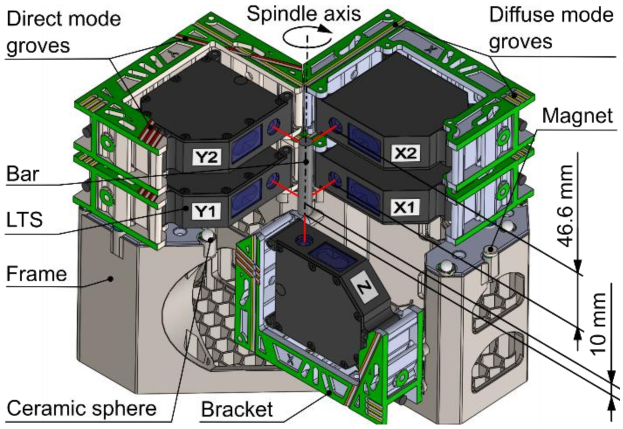

Figure 2. LTS setup for measurement on a 10 mm bar in diffuse mode.

2.3. On-machine alignment procedure

To characterize the thermal behavior of a machine tool, a calibrated bar is mounted on the spindle and placed in front of the five LTSs as shown in Fig. 2, and its displacement is measured over time. However, the measured distance to the bar does not contain any information about the measurement location and therefore coplanarity of spindle axis and laser beam cannot be assumed. To describe the linear displacement signal as measurement position in the machine space, the laser beam direction vector u and the sensor's zero position P_0 at start of measuring range (SMR) must be known for each sensor. Calibration methods in the context of laser triangulation on-machine measurement technology (LTOMM) have been presented, where a calibrated sphere on the machine table is scanned with a LTS mounted on the spindle [6,7].

In this work, an incremental laser origin and direction scanning method without synchronous reading of the machine positions was developed to enable a quick installation on various machines independent on their control type. The method uses a probe-like artifact with spherical tip mounted on the machine spindle and consists of three steps: i) arc profiles of the sphere are probed on multiple positions along the laser beam; ii) a line and thus the laser beam vector u is fitted to the intersecting circles; iii) the measured distances are used to determine the origin P_0. A profile of the artifact's spherical tip, consisting of a steel sphere with a diameter of 10 mm, is probed with the laser beam by moving it along one of the two machine axes, which are quasi perpendicular to the direction of the laser beam, while recording the distance values. The measured distance profile along the sphere is a circular arc with unknown diameter due to the misalignment between the laser beam and the machine axis along which the LTS is oriented, indicated in red in Figure 3a. The measured arc profile lies in the plane spanned by the scanning direction v and the laser beam direction u. However, point I on the scanned profile, at which the smallest distance value is measured, lies in the plane that passes through the center of the sphere C perpendicular to the scanning direction v (green in Figure 3a). Thus point I is part of a circle with radius r, normal vector v and center point C, whose position is known in machine coordinates. The measurement is repeated along the second

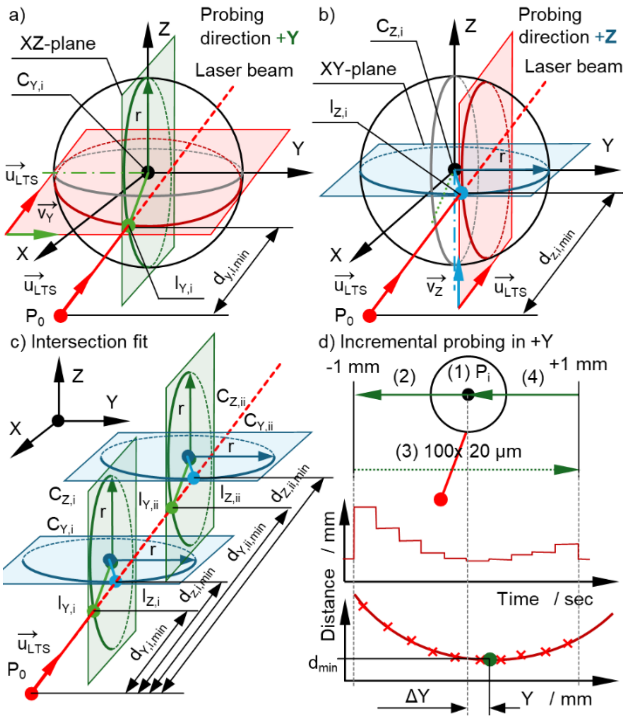

Figure 3. Sphere profile probing principle illustrated for the laser direction in X: a) Scanning along the Y-axis; b) Scanning along the Z-axis; c) Circle set in space intersected by laser beam and probed distances to origin P_0; d) Incremental moving strategy and data analysis.

quasi perpendicular machine axis to the laser beam u, as shown in Figure 3b. With measurements at various positions i along the measuring range of the LTS, a set of circles is obtained in space which are all intersected by the laser beam, as shown in Figure 3c. This line and thus the location of the intersection points I is determined by using a best-fit where the distance of the line to the circles is minimized. The origin P_0 is determined as the mean of the intersection points I, which are shifted along the laser direction u by the measured minimum distance d_{min}.

To determine the position of the sphere centre C during the measurement without synchronous reading of the machine axis positions, the sphere is moved in incremental steps in front of the LTS. First the minimum distance position is manually determined at mid of measuring range P_{MMR} and stored for each LTS as reference point in the machine control. Subsequently, six profile measurements are taken per LTS at three different distances from P_0 along the measuring range at 0.2 mm, 1 mm and 1.8 mm using a NC-routine. For each measurement, the sphere is: *i)* placed at its starting position P_i; *ii)* moved by -1 mm in the scanning direction; *iii)* incrementally moved to +1 mm in +20 µm steps with 1 second waiting time in between; and *iv)* returned to P_i. This results in 101 measurement points per run including the starting point of the 2 mm travel, illustrated in Figure 3d. The measured distance profile is recorded. The signal is stepped while the arc is sampled over the 2 mm stretch, segmented for each sampling position, and averaged over 0.3 sec, starting at the center of the signal segment to avoid unstable areas due to the spindle movement between each sampling step using MATLAB R2022b. As the starting point P_i for each incremental profile scanning run is known in relation to P_{MMR}, the 101 distance points are assigned to the sphere position in scanning direction. By fitting a circle with unknown diameter to the points, the shortest distance d_{min} and the offset of the circle centre point to the reference point P_{MMR} in scanning direction are determined.

2.4. Continuous measurement on rotating spindle

A calibrated tungsten carbide bar is mounted on the spindle and placed at mid measurement range (MMR) in front of all five

LTSs. Spindle speed is selected to the operator's choice. The distance signals, sampled at 20 kHz, contain the oscillation resulting from the radial runout of the bar and noise due to optical effects on the bar surface. Such oscillations are canceled out by averaging the signal every 0.5 seconds, thus a data point contains multiple rotations. A resolution of 2 Hz is sufficient to characterize the thermal behavior of a machine tool.

As five points on the bar are known in space, the rotational axis of the spindle at any time instance is calculated by fitting a cylinder with 10 mm diameter to the four points measured in X- and Y-direction. The displacements in X- and Y- direction are calculated at two constant Z-heights, called L2 between Z_{Y2}, Z_{X2} and L1 for Z_{Y1} and Z_{X1}. The angular drift to the initial spindle position is calculated through the differential displacements at L1 and L2. The displacement in Z is calculated by the intersection of the rotation axis with its normal plane through the point measured in Z. This method enables continuous measurement of the spindle rotation axis instead of assuming its position.

3. Results

3.1 Thermal stability of LTS

One LTS was clamped on a granite table measuring the distance towards a granite block over 16,5 hours in a temperature-controlled environment, as shown in Figure 4a. The ambient temperature was measured by the Extech RHT20 temperature datalogger with a resolution of 0.1 K and the temperature on the sensor housing with a thermocouple logged with a NI-9213 module with a resolution of 0.3 mK. The results are shown in Figure 4b. The LTS stabilizes after a heat up phase of 2 hours and a distance offset of 10.5 µm. The decrease in the ambient temperature of 0.8°C over the remaining measurement period led to a concurrent temperature decrease on the sensor casing by 1.0°C and an increase in the measured distance to the granite block by 1.5 µm. It is considerably greater than the temperature stability of ±0.01 % FSO/K specified by the manufacturer [4], which corresponds to 0.2 µm, as it also includes the shrinkage of the measurement setup.

3.2 Direction and origin detection

The measurement setup was placed on the table of a 3-axis machine tool. The laser direction and origin were determined twice for all five LTSs according to the method described in section 2.3, labeled as run 1 (r1) and run 2 (r2). The variation in X, Y and Z of the laser origins P_0 and laser direction unit vectors u and the resulting distance d and angle α between the laser beam pairs are listed in Table 1. The maximum deviation between the two measurements is 4.7 µm and 168 arc seconds.

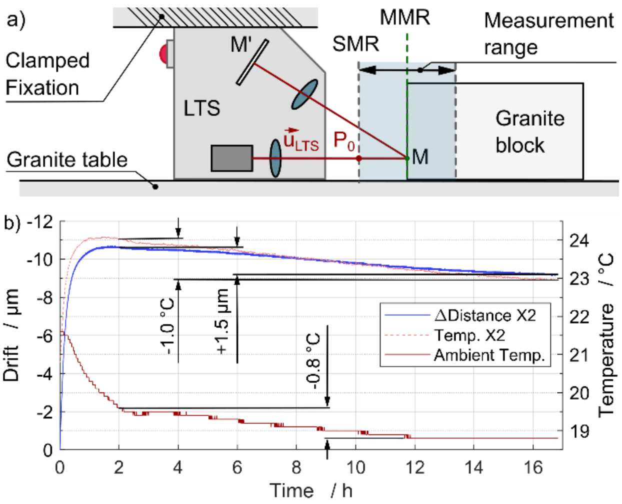

Figure 4. Thermal drift measurement of LTS X2: a) setup; b) results.

Table 1 Difference between two consecutive LTS calibration runs.

	$\Delta P_{0,x}$	$\Delta P_{0,y}$	$\Delta P_{0,z}$	d	Δu_x	Δu_y	Δu_z	α
	µm	µm	µm	µm	$\cdot 10^{-4}$	$\cdot 10^{-4}$	$\cdot 10^{-4}$	arc sec
X1	-0.7	0.2	0.4	0.9	0.0	-0.6	3.8	78
X2	-0.6	0.6	1.5	1.7	-0.0	1.9	-1.9	55
Y1	0.4	-1.7	0.4	1.8	0.0	0.0	4.4	90
Y2	0.1	4.7	0.4	4.7	-1.3	0.0	1.3	36
Z	2.1	-1.1	-3.7	4.4	-8.1	0.6	-0.0	168

3.3 Spindle drift over time

The setup was used to characterize the spindle displacement and inclination and the efficiency of the thermal compensation strategy of a 3-axis machine tool with a C frame construction at 15000 rpm. The measurement was performed on a calibrated 10 mm carbide bar over 104 minutes with a cold spindle at the start. After 101 minutes, the compensation in Z-direction, and after 102 minutes the compensation in Y-direction were deactivated. The results are evaluated for three laser position sets, r1 and r2 and the theoretical LTS positions according to the CAD model (CAD), on which the bar position in space cannot be corrected.

The spindle displacements in X-, Y-, and Z-direction are shown in Figure 5a, the spindle inclination in XZ- and YZ-plane in Figure 5b and the difference in displacements over time compared to laser position set r2 in Figure 5c. The zero point was set to 0.75 sec, where full rotational speed was reached. However, the zero point depends on the residuals of the fit, which is highest in the first few points, which can lead to a jump in the curves at the beginning. The results for the two probed LTS position sets in space r1 and r2 agree well and their difference ($\Delta X_{1,r1}$, $\Delta X_{2,r1}$, $\Delta Y_{1,r1}$, $\Delta Y2_{,r1}$) is of the same magnitude of the residuals of the cylinder fit on the four points is space.

The correction due to the probed laser positions in space (r2) can be seen in the difference to the CAD results compensating for the errors due to off-center measurements positions on the bar to the extent of 2 µm at Y1 and 1 µm at X1 over the first 101 minutes. In this period, the results display the residuals of the machine thermal compensation strategy at 15000 rpm and after 102 minutes the uncompensated spindle position. The spindle displacement by 9 µm due to the deactivation of the compensation in Y is 1 µm less than displayed in the machine control but is only attributed to Y_{L1} and Y_{L2} when correcting for the LTS positions in space, compared to 1.8 µm in $X_{1,CAD}$ and $X_{2,CAD}$. The largest spindle displacement occurs in the Z-direction, which amounts to 19.3 µm after 101 minutes and increases to 48.6 µm after deactivating the compensation. The drop by 29.3 µm agrees well with the 29 µm displayed in the machine control. The correction in Z due to the inclination of the front surface of the bar and of centered measurement position is negligibly small. The inclination curves for the two probed LTS position sets in space r1 and r2 in Figure 5c agree well. The gradual rise of inclination in the YZ-plane α_{YZ} by 25 arc seconds is twice as large as the inclination in XZ-plane by -12 arc seconds.

4. Discussion and Conclusion

The presented setup, the measurement method and the data analysis are subject to uncertainties. The establishment of the uncertainty budget is ongoing work. The goal is to perform a spindle thermal characterization with full uncertainty budget. The most influential error contributors, specifically the ambient temperature, machine tool repositioning accuracy, sensor specific errors such as speckle noise and inclination error have been identified and are briefly discussed in the following.

The measurement setup used is subject to thermal effects. To avoid the drift during the start phase of the sensors, shown in

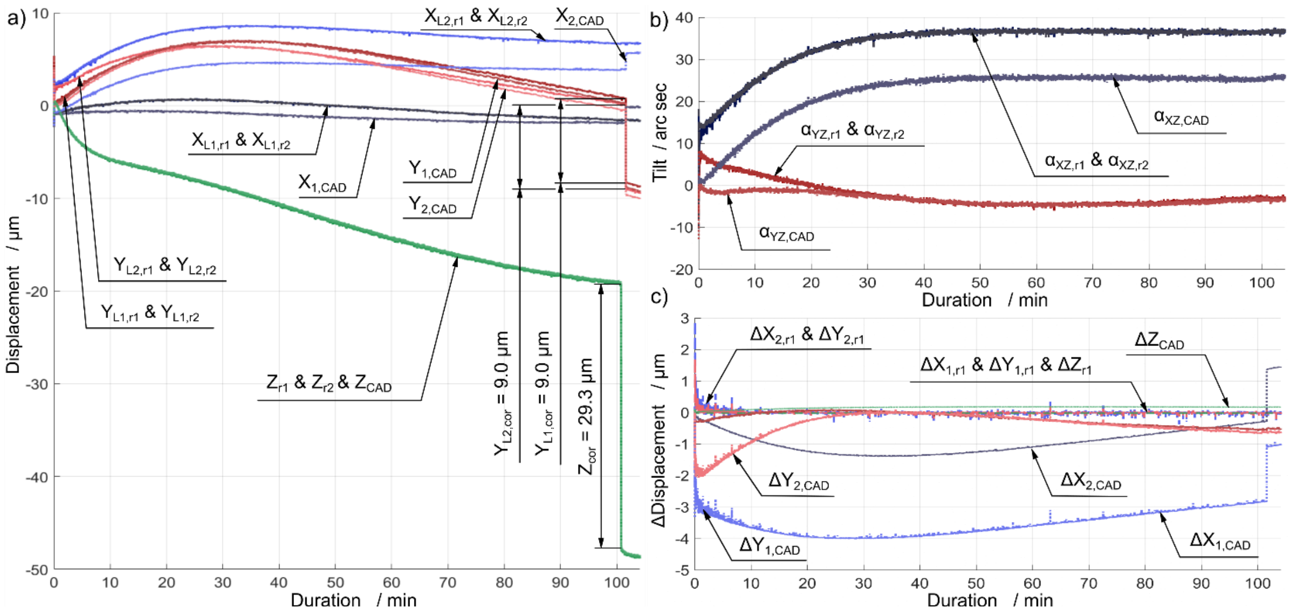

Figure 5. Thermal drift measurements of spindle displacement at 15000 rpm in relation to laser positions probed on-machine in run 1 (r1), reference run 2 (r2), and positions in the CAD-model (CAD): a) Displacements; b) Angular tilt; c) Difference of displacement values to reference run 2 (r2).

Figure 4b, the sensors must be switched on 2 hours prior to the measurements. In addition, the frame and the tool steel brackets expand when the temperature changes during the measurements. For reference, the expansion of the frame made of tool steel with a coefficient of thermal expansion (CTE) of 10 µm/(m K) [7] in X, Y, and Z for 1 K uniform temperature change is 2,1 µm, 2,4 µm, and 1,3 µm. This will be addressed in a future step where the frame will be equipped with thermocouples to continuously record the temperature during the measurement. By simulating the thermal expansion of the setup using the finite element method (FEM), from the results of which a metamodel can be derived, the deformation of the frame structure and thus the displacement of the sensors as a function of temperature can be calculated and compensated for in real time. Nevertheless, at present, great attention should be paid to temperature stability in the measuring room.

There are sensor-specific limitations to the data acquisition accuracy of LTSs. Inclination errors due to a non-perpendicular alignment of the laser beam to the inspected surface can be quantitatively calculated based on a mathematical model derived from the optical triangulation principle, the object equation of the optical path relationship and the deviation of the laser point center allowing to compensate for the error [8]. The speckle effect is a granular noise on the analyzed light spot texture degrading the signal quality of coherent imaging systems as a consequence of interference among wavefronts on surfaces [9]. This error is superimposed as noise on the signal with amplitudes depending on the object's surface topography [10], and is repeatable due to the optical interference as a result of the surface characteristics. On rotating objects, such as the calibrated bar during the presented thermal drift measurement, the repeating pattern of the speckle noise per rotation is canceled out. The influence of speckle noise on the data analysis can be further reduced by low-pass filtering of the measurement signal [7], and calibrated measurement objects with surface roughness values between 0.4 µm to 3 µm Sa [10].

A crucial part of the presented method is the assessment of the LTS alignment quality and repeatability to determine its influence on the measured quantities which despite the speckle effect is also influenced by the machine positioning accuracy. While machine tool positioning accuracy affects the estimation of the laser beam directions and thus of the spindle thermal deformation, spindle thermal compensation with an accuracy better than the machine positioning accuracy is not required as finer displacements cannot be controlled by the machine.

The runout and speckle noise contributions are removed in the presented data analysis by averaging the sensor signal over a period of 0.5 sec containing 125 spindle rotations.

The presented frame setup has proven its viability as a robust and cost-effective solution to characterize spindle elongation in machine tools and characterization of compensation strategies according to ISO 230-3. Tests have been performed at different industrial partners in the context of the Erasmus+ project PREFAM [11], proving suitability for machine spindle thermal characterization as well as educational on-site activities.

Acknowledgement

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