Increasing 5-axis accuracy by using a cross-grid encoder for volumetric compensation

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Abstract

The volumetric compensation of small precision machine tools is demanding because of the limited space available for placing measurement instruments and the required measurement accuracy. Therefore, we introduce a procedure to measure and compensate the volumetric error for the three linear axes with a traversing range up to 210 mm. The measuring device is a highly accurate grid encoder with a short-range error below 40 nm and a global accuracy better than 1 µm. We show the improvement of volumetric accuracy and demonstrate the need for a volumetric calibration of the linear axes for five-axis accuracy. The improvement of accuracy is illustrated by measurements as well as on a five-axis test workpiece.

1 Accuracy and reproducibility of a small 5-axis machine tool

Small 5-axis machining centres are commonly used in a variety of industrial sectors. Industrial applications include medical technology for artificial joints and dental prostheses, the automotive industry with impellers for turbomachinery, and in particular, die and mold making. This is one of the key technologies for the automotive and consumer goods industries, where the trend is toward miniaturisation and functional integration with a simultaneous shortening of product life cycles. This in turn influences the requirements for die and mold making. Components gain in complexity due to functional integration, and manufacturing tolerances become tighter because of miniaturisation. Simultaneously, iteration loops are removed from production processes to reduce lead times and to more rapidly output products to markets. A demand has arisen for high-performance, 5-axis machining centres with smaller production uncertainties.

There are a number of reasons for such production uncertainties, including static geometric deviations on machine tools, which is one of the largest error sources. Errors can be subdivided into systematic and statistical errors, whereby the former can be reduced by the implementation of compensating procedures. The necessary requirements for compensation are:

- Statistical machine errors are low compared to systematic machine errors
- Measuring uncertainty in the identification of errors is low compared to systematic machine errors
- The machine must be capable to transmit small compensation movements to the TCP

Statistical errors limit repeatability, whereby repeatability constitutes the foundation for successful compensation of the machine tool. KERN Microtechnik uses different approaches for ensuring repeatability, as described in [1]. The focus in this regard is on the thermal behaviour of the machine, thermal drift being kept to minimum levels via temperature management. This in turn lays the foundation for successful compensation measures.

2 Volumetric error compensation in the machine tool

The static volumetric precision of an axis arrangement with multiple axes is fundamentally influenced by the precision of its individual axes. Errors in single axes accumulate on the TCP and generate position and orientation errors. This error at the TCP is influenced by the position of all axes. Thus the configuration space is an n-dimensional space (n = number of affected axes). Two methods, in principle, apply to compensate for such errors on machine tools:

1. Direct measurement of errors in the working space and compensation via multi-dimensional table interpolation
2. Model identification with less measurement complexity and compensation via error model

Parameterising a table interpolation for a 3-axis machine is already highly complex in terms of measurement technology. Positions must be measured with sufficient accuracy for the complete working space at the desired measuring point distances, this being hardly possible with the current measuring technology. If significant different tool lengths are used also orientations have to be measured.

An alternative method is the identification of a rigid body error model. This is possible with various forms of measuring technology [2]. The measuring complexity for identifying this model is significantly less. The precondition for this process is that the rigid body error model is able to map the volumetric error with sufficient accuracy.

3 Rigid body error model

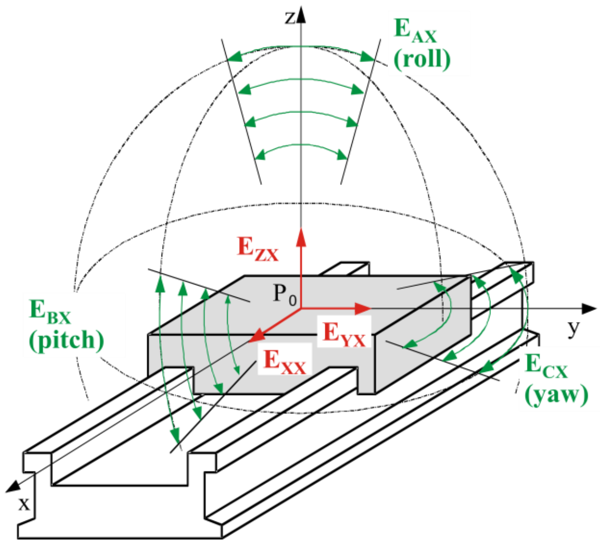

Figure 1: Component errors of a linear axis

The rigid body error model is specified in ISO 230-1 [3]. The errors of an axis are subdivided into position and orientation errors (location errors) and linear and angular error motions (component errors). Location errors specify the deviation of the mean axis position from the ideal position of an axis in the space. Component errors specify the deviation of an axis motion from the ideal motion in all six degrees of freedom. Component errors depend on the position of the axis.

Figure 1 shows the component errors for the x-axis. These consist in detail of one linear positioning error (E_{XX}), two straightness errors (E_{YX}, E_{ZX}) and three angular error motions (E_{AX}, E_{BX}, E_{CX}). Corresponding location and component errors also exist for rotary axes. For an arrangement of three linear axes, this leads to three effective location errors of the linear axes and 18 component errors. Component errors are functions depending on axis positions, and these can be saved as formulas or tables for control compensation purposes.

4 High-accuracy cross grid encoder

The identification of component errors from specific measurement data in the working space places high demands on the encoder. The basis for the process outlined here is the measurement of two-dimensional deviations with the high-precision HEIDENHAIN KGM 282. This system has a short-range error of less than 40 nm and a global accuracy of better than 1 µm in both dimensions.

Figure 2 shows the absolute two-dimensional error of a KGM at a maximum of 300 nm.

To keep this accuracy reproducible, the glass plate accommodating the precision scale is mechanically decoupled from the mounting surface via a three-point contact. This in turn ensures that measuring accuracy is not influenced when the KGM is mounted in the working space.

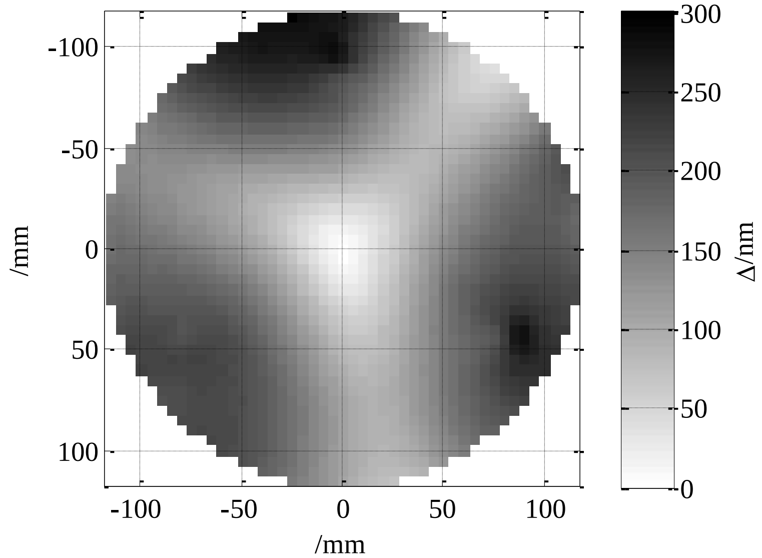

Figure 2: two-dimensional accuracy of a grid encoder in the measuring plane

5 Calibration process with cross grid encoders

Special requirements exist for the measurement and parameterisation of volumetric compensation with compact machine tools, because the encoders are often too large to fit into the working space with axis lengths of 200 mm. We therefore outline a process whereby a rigid body error model of a compact, 3-axis machine tool can be identified.

Reference [4] shows a process for ascertaining the component errors of a machine tool. Yang and others identify component errors in the form of polynomial approaches by measuring circles and straight lines on the cross grid encoder. Location errors and component errors are determined sequentially. As an alternative, we present a process identifying the component errors at location-discrete sampling points, minimizing the measured total error in a single step. The number of sampling points can be varied via the density of measured points, in turn significantly improving the local resolution of the component errors.

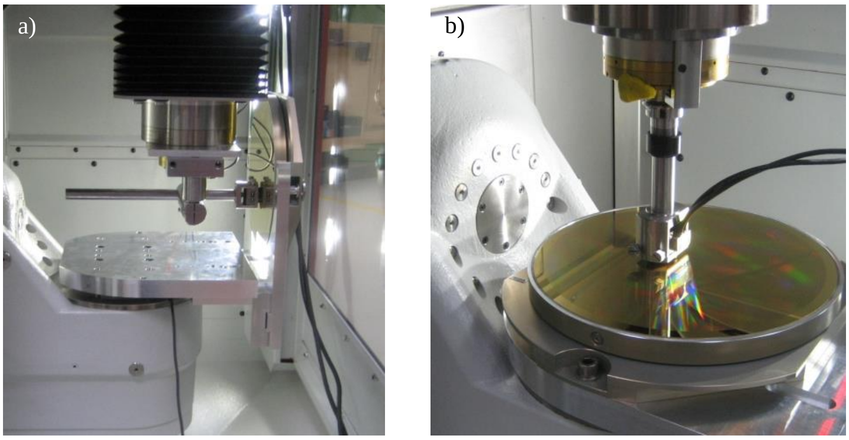

Figure 3: KGM measurement setup for the y-plane and z-plane

The complete measurement for the identification process is achieved with only six setups. This is the advantage compared to the method introduced in reference [5]. These six setups use only four mounting positions for the cross grid encoder. Figure 3 shows the mounting position in the y and the z planes. For a five-axis machine, the cross grid encoder can be easily remounted from the x to the y plane by turning the machine table. This reduces the mounting and measuring time of the procedure. As in reference [5], the exact position and in-plane rotation of the KGM need not be adjusted. It is later determined by the identification algorithm. One or two measurements have to be taken, depending on the plane in which the grid encoder is mounted. A single measurement consists of several evenly distributed points. These points are measured twice along a path in forward and backward direction. In two single planes, the measurements vary only in different offsets of the scanning head to the tool reference point (spindle nose). This is achieved by a special fixture. In one plane, two mounting positions of the KGM are necessary. The distance of the support points for the identified component errors is linked to the distribution of the measured positions on the KGM. Figure 4 shows the necessary NC paths and the path of the readout head on the KGM for a machine with an axis order of w-X-Y-Z-t. It can be seen that in this case two mounting positions of the grid encoder for the z plane are necessary.

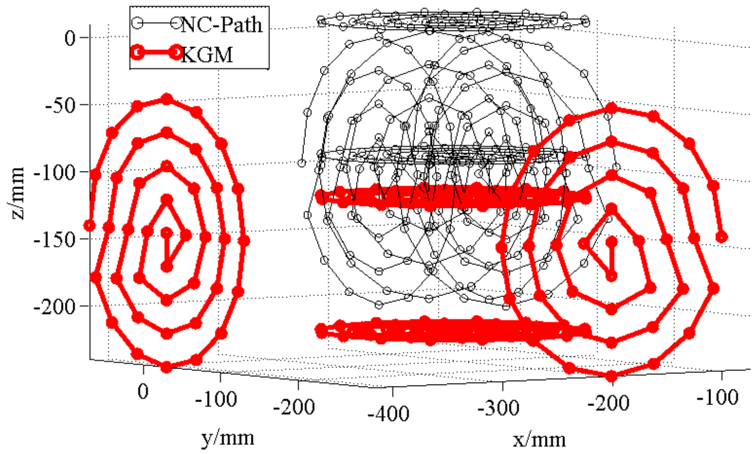

Figure 4: Path of measurements for 3-axis calibration

6 Results of 3-axis calibration

The result of compensation can be determined directly from the raw data of deviations measured on the KGM. Figure 5 shows all measured 2-dimensional deviations. The maximum deviation in all planes is 14.9 µm before calibration, and 1.5 µm following compensation of the identified model. Therefore, the result is only slightly above the residual error of 1 µm that cannot be described by the rigid body error model.

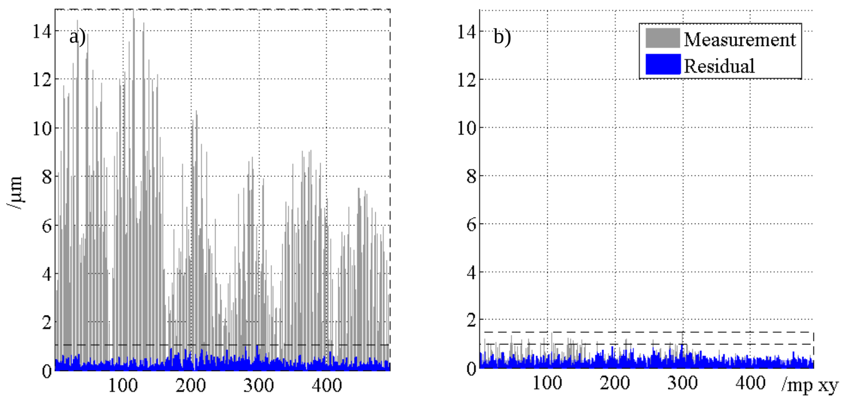

Figure 5: Absolute in plane deviation measured before a) and after b) compensation.

Measurement data variance with active compensation is 1.8 µm (k =3). Table 1 lists the individual measurement uncertainties. It was found that the small measurement error of the cross grid only has subordinate influence on the total error. In contrast, the forward backward deviation of the current measurements is the largest source of error. Improvements to the mount of the scanning head on the TCP should provide the largest potential for optimisation to achieve a complete measurement uncertainty of 1.0 µm (k=3) in the future.

Table 1: Measurement uncertainty (k=3)

	actual/µm	aim/µm
Translatory thermal drift stability within 7 min.	0.2	0.2
Position error of KGM	0.16	0.16
Forward backward (mounting + machine)	1.65	0.8
Other effects	0.7	0.6
Total (k = 3)	**1.8**	**1.0**

The effects of the identified rigid body error model on the working volume measured are shown in Figure 6. Without any compensation, spatial errors of up to 20 µm must be expected. After compensation, the largest calculated volumetric errors from the identified model are below 2 µm.

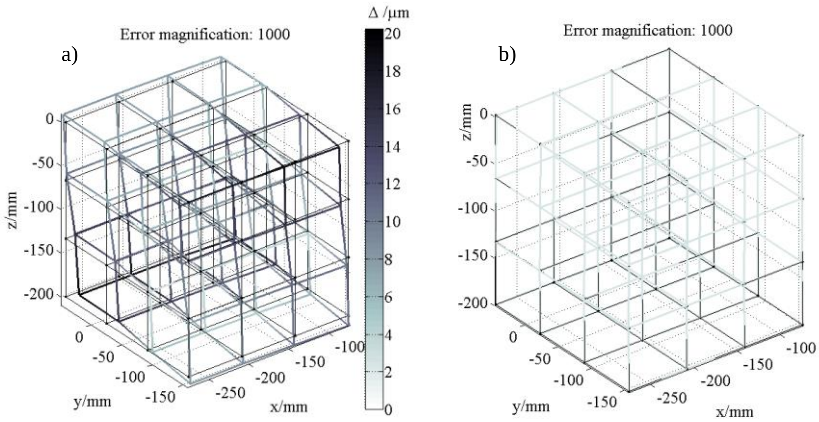

Figure 6: Volumetric errors calculated from a rigid body error model before and after compensation

7 Five-Axis calibration of position errors for the rotational axis

Location errors of rotary axes on machine tools are generally determined by probing a calibration sphere mounted on the machine tool table with a touch probe (Figure 7). The position of the sphere in the machine coordinate system is measured at various rotary axis positions and compared with the nominal position. An optimisation process identifies the position errors of the rotary axes by minimizing the measured errors.

Figure 7: B-axis calibration with touch probe and calibration sphere

With this measurement process, the machine coordinate system is defined through the linear axes. Hence the accuracy of the identified location errors of the rotary axes depends on the accuracy of the linear axes. Without volumetric compensation of the linear axes, the identification of the location errors is dependent on the positioning of the measurement sphere on the machine table. To inspect this, a B axis is calibrated twice, whereby the calibration sphere is offset by 100 mm on the table in the y direction. Table 2 lists the differences of the specifically identified location errors in accordance with ISO 230-1 [3]. The last row shows the maximum volumetric error resulting of a calibration in one position and measuring in the other position. If the linear axes are not volumetrically compensated, the second measurement results in a maximum spatial error of 22.3 µm. With volumetric compensation this error can be dramatically reduced to 2.8 µm. Precise and robust rotary axis calibration with touch probe and calibration sphere is therefore only possible if the linear axes were previously volumetrically compensated.

Table 2: Calibration of location errors of rotational B axis with and without volumetric compensation of the linear axis

Difference of identified location errors	Vol. compensation of linear axis	No vol. compensation of linear axis
Δ E_{Z0B}/µm	2.2	13.4
Δ E_{X0B}/µm	0.2	2.4
Δ E_{A0B}/µrad	3.8	13.4
Δ E_{C0B}/µrad	1.0	3.6
Δ Max. vol. error/µm	**2.8**	**22.3**

8 5-axis test workpiece

Many methods exist for the indirect characterisation of 5-axis machine tools by producing a test workpiece. Here we would like to outline one of these. The production of this test workpiece has been set up so that as many geometric machine errors as possible affect the total errors on a specific reference plane. The following influences prevail: Position errors of the rotary axes, component errors of the linear axes, thermo-elastic machine deformations and deviations in the tool geometry.

Figure 7 shows the workpiece. The decisive feature is the square face on the upper side, with dimensions of 40 x 40 mm. The surface is subdivided into 4 x 4 = 16 squares, all lying in a single plane. All squares are machined with the same tool—a ball-nose cutter with radius R = 1.5 mm.

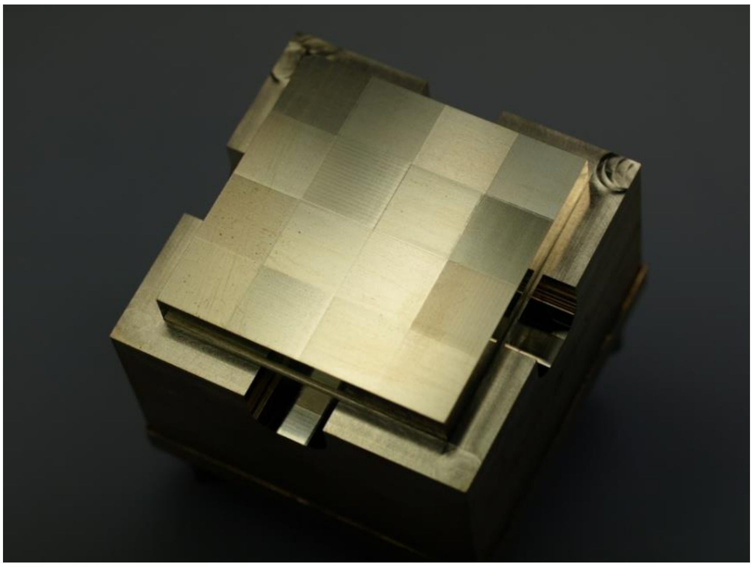

Figure 7: 5-axis test component

The surfaces are machined by multipass milling with various angles of incidence of the rotary and swivel axis. The angle of inclination of the cutter varies between 0° and 75° during machining, and the swivel range of the B and C axis is therefore between 0° to 75° and 0° to 270°. Production of the workpiece requires approximately 20 minutes. After machine calibration, a smoothness of ±2.7 µm is achieved over the complete plane. This result demonstrates that the machine has high absolute 5-axis accuracy as well as very high reproducibility. The kinematics of the machine can be identified with the specified process, whereby volumetric errors are optimally compensated.

9 References

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