Accuracy enhancement of five-axis machining by controller based compensation

C. Brecher[1], J. Flore[1], J. Behrens[1], C. Wenzel[1]
[1]*Fraunhofer Institute for Production Technology IPT, Germany*
jan.behrens@ipt.fraunhofer.de

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Abstract

This paper represents investigations to reduce the required calibration and compensation effort for machining accuracy enhancement by identifying and treating significant axis errors that have superior impact on the accuracy. For this theoretical and metrological analyses were performed as well as machining tests.

1. Introduction

The machining accuracy of 5-axis machines is affected by numerous geometrical errors of the machine axes [1, 2]. The metrological calibration, compensation and verification of all errors in order to enhance the machining accuracy result in extensive time and device related efforts [2]. By means of a systematic analysis of the error impacts the potentials for an effort reduced enhancement can be identified.

2. Sensitivity analysis of error budget

As a basis for all subsequent simulations and analyses a geometric and kinematic five-axis machine model was created that considers all geometric errors of the machine axes [1, 2] and represents the transformation of the single axis errors on the volumetric error. This model is build up by combining basic equations that represent the geometric and kinematic behaviour of translational and rotational machine axes.

The impact of each single axis error on the volumetric machining accuracy depends on the geometric and kinematic properties of the machine. By a sensitivity analysis that based on the described machine model the impact of each single error can be determined. Figure 1 represents the results of this analysis for a demonstrator five-axis machine (axis configuration: CAYXZ, size: (800 x 800 x 600) mm^3.

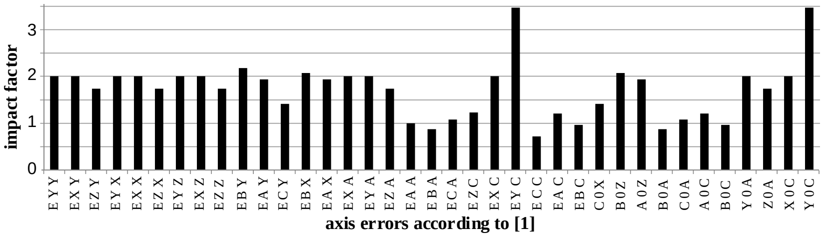


Figure 1. Impact factors of axis errors on volumetric machining accuracy

3. Identification of rank orders for effort reduced error compensation

The presence of axis errors with minor impact suggests that significantly optimised machine accuracy can be realised by just calibrating and compensating these errors that have a superior impact. However these impact factors do not consider the real error amount. To further analyse this idea some exemplary error budgets have been defined as well as four different rank orders that represent the error grouping of an iterative compensation in five steps (step one = no compensation, step five = full compensation). Table 1 summarizes the rank orders and its ranking criterions.

Table 1. Rank orders for error compensation

rank order	ranking criterions
A	impact factor
B	multiplication of maximum error value and impact factor
C	simulation of maximum error influences on machining accuracy for each error separately
D	"common assumption": superior impact of positional errors and location errors

4. Limitation of compensation due to uncertainty

The compensation of axis errors is limited by measurement uncertainty [2] of the calibration procedure as well as machine axis repeatability. To identify the volumetric error due to not correctable uncertainty and repeatability (= limitation of compensation) simulations based on the above described machine model has been performed in which the axis errors are modelled by random values of defined intervals. As examples: for the interval ± 1 µm and ± 1 µrad the maximum volumetric error is 8 µm for ±3 µm, ± 3 µrad the error is 28 µm and for ± 5 µm and ± 5 µrad the error is 43 µm. Consequently the reliably achievable machining accuracy cannot be more precise than the volumetric error due to the given uncertainty and repeatability.

5. Validation by means of measurements

To identify the volumetric error of the demonstrator five-axis machine a measurement procedure designed following to the “Chase the Ball” [3] procedure was used. For each measurement a specific error table according to the error budget and rank order was activated in the controller. A reference measurement without any error table represents the accurate machine. Figure 2 shows the results of the compensation tests including the above discussed limitations. If some rough information about the errors is available (e.g. max. amount) an accuracy enhancement about 80 % can be realised (rank order B) by just calibrating and compensating the half of the total error budget.

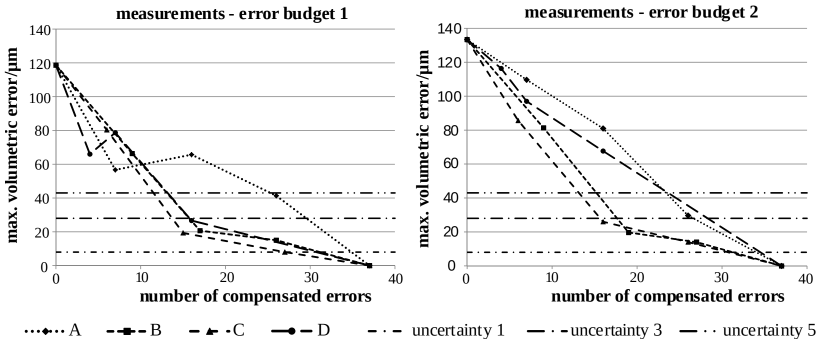
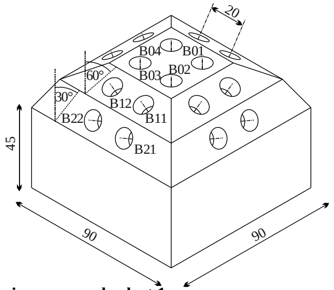


Figure 2. Metrological results of error compensation

6. Validation by means of work piece machining

To validate the measurements test work pieces were designed and machined. The relevant testing geometries are milled boreholes. The neighboured boreholes were machined by rotating one of the rotary axes minimum 90°. Further the work pieces were mounted eccentric to the rotary axis centres. Hereby the axes moved to significant different positions and the available machine volume and axis ranges were integrated as best as possible. Figure 3 shows the work piece design and indicates the explained machining procedure (table). The work pieces were machined using the same machine and the same compensation procedure as for the measurements. A reference work piece was machined without any error table. Thereafter the work pieces were tested on a five-axis CMM. For each milled borehole the midpoint coordinates were identified and the maximum deviation to the reference calculated.

Figure 3 shows the results for both error budgets and each compensation rank order. It can be stated that the machining tests confirm the measurements and its findings.



	A/°	C/°
B01	0	0
B02	0	90
B03	0	180
B04	0	270
B11	30	0
B12	-30	180
...	...	...
B21	60	0
B22	-60	180
...	...	...

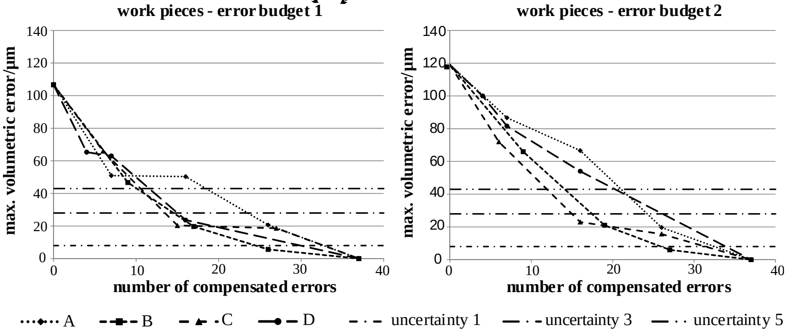


Figure 3. Design of test work piece and CMM testing results of machining

7. Conclusion and Outlook

The achievable machining accuracy is limited by uncertainty and repeatability. Accuracy can be enhanced significantly by just treating errors with superior impact. For this the maximum error amounts should be known roughly. The development of a testing procedure for the fast error amount estimation will make this possible.

Acknowledgement

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References:

[1] ISO 230-1 international standard 1999 Test code for machine tools part 1
[2] Schwenke H, Knapp W, Haitjema H, Weckenmann A, Schmitt R and Delbressine F 2008 Geometric error measurement and compensation of machines - an update *Annals of the CIRP* vol. 57 p 660-75
[3] Bringmann B and Knapp W 2006 Model-based ‘chase-the-ball’ calibration of a 5-axes machining centre *Annals of the CIRP* vol. 55 p 531-4