Systematic analysis of 5-axis machine error budgets: Decreasing the calibration effort without decreasing the machining accuracy

C. Brecher, J. Flore, C. Wenzel
Fraunhofer Institute for Production Technology, Germany

Abstract

An efficient 5-axis machining process requires a recurrent metrological calibration and controller based compensation of the machine axes to capacitate a sustained machining accuracy. However the metrological identification of the geometrical axis errors still necessitates a huge time and device related effort [1]. Consequently the goal of current research work is to reduce the necessary metrological effort without decreasing the achievable improvement of the machining accuracy.
This paper deals with an approach for systematic analyses of the axis error impact on the overall 5-axis machining accuracy. The bases for the analyses are mathematical models that represent the transformation of the single axis errors on the overall three-dimensional machining accuracy. Within systematic analyses the impact of each single axis error can be evaluated independent of the error amount but in consideration of the axis configuration, the machine size as well as further parameters like tool and work piece size. The results show that the specific impact depends particularly on the machine size and the axis configuration.
Besides this a metrological approach will be presented that capacitates the validation of the impact analyses results. This approach also gives the chance to realise a quick check calibration procedure by exploiting the developed mathematical models and the information about inferior and superior errors.

1 Introduction

5-axis machine tools are powerful in terms of machining complex geometries within a short period of time and without disadvantageous clamping operations [2]. On the other hand the increased number of axes and their geometrical axis

errors (caused by production and assembly of axis components) result in general in a reduced overall precision compared to 3-axis machine tools [3]. Consequently to ensure efficient machining processes the geometrical properties of a 5-axis machine axis system have to be calibrated metrologically and improved by means of controller based compensation recurrently.
However the metrological effort is still huge because a lot of deviations in the form of axis error have to be identified. Each single linear or rotary axis is characterized by six geometrical errors of motion (Fig. 1, left side) according to the six degrees of freedom of a moving rigid body [4]. Reasons for these geometrical motion errors are imperfect geometry and dimensions of machine components [1] or wear [5]. To describe the overall accuracy of a multi axis machine, the error functions of several axes have to be considered depending on the given axis configuration. Herein further geometrical errors of the axis system like orientation deviations of the axes as well as offset errors have to be considered [1] (Fig. 1, right side). Depending on the calibration model, a 5-axis machine is characterised by up to 52 single axis errors [6].

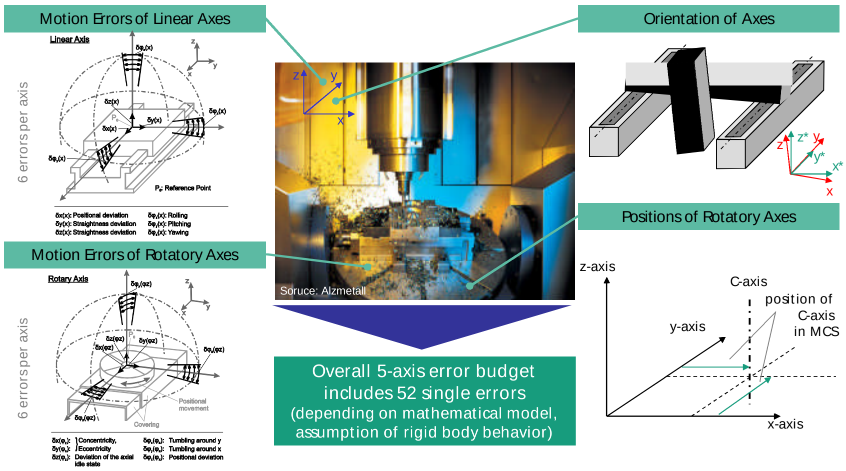

Figure 1: Composition of the error budget of 5-axis machine tools

However within the design of compact and precise 5-axis machines it can be evidenced, that specific errors have an inferior impact on the overall machining accuracy depending on the axis configuration and machine size [2]. According to this context, within on-going research work, the authors investigate in the analyses of 5-axis machine error budgets. The aim is to identify machine specific axis errors that have only an inferior impact on the machining accuracy. For this capable mathematical machine models are used. Furthermore the goal is to investigate if inferior axis errors can be neglected within the calibration and compensation procedure without decreasing the achievable improvement of machining accuracy. For this a lot of simulations as well as practical, metrological tests have to be performed. The first results of this project are presented in this paper.

2 Geometrical error modelling of 5-axis machine tools

The modelling of 5-axis machines started in the 1990 [7]. Most of the models based on the utilization of 4x4 homogenous transformation matrices (HTM) [8] or on the utilization of separate 3x1 vectors for the translational and 3x3 matrices for the rotary motions [4]. However the created models of multi-axis or 5-axis machines, described in papers differ depending on the considered axis errors. For example, Schmitt et al. [9] modelled the 5-axis system by 34 errors whereas [10] considers 41 errors. Within this paper the models base on 3x1 vectors for the translational and 3x3 matrices for the rotary motions. 42 single errors will be considered. The errors of the spindle are neglected.

2.1 Basic equations for modular modelling

For the error modelling of a single axis two basic equations, one for a linear and another one for a rotary axis have been developed. Based on a vector chain description (Fig. 2), the real position $\mathbf{x}_L(x)$ of an observed point on a linear axis (given by $\mathbf{l}_x$) described in an axis external reference system is:

$$\boldsymbol{x}_{\mathrm{L}}(x) = \mathbf{O}_{\mathrm{x}}\left(\boldsymbol{n}(x) + \Delta\boldsymbol{t}(x) + \Delta\boldsymbol{R}(x)\cdot\mathbf{l}_{\mathrm{x}}\right) \qquad (1)$$

The 3x1 vector $\Delta\mathbf{t}(x)$ represents the translational axis errors (positional and straightness deviations), the 3x3 matrix $\Delta\mathbf{R}(x)$ the rotational errors (roll, pitch, yaw), the 3x1 vector $\mathbf{n}(x)$ the nominal axis position and the vector $\mathbf{l}_x$ the position of the observed point. By $\mathbf{O}_x$ (3x3 matrix) the orientation between the linear axis coordinate system and the external reference coordinate system is described.

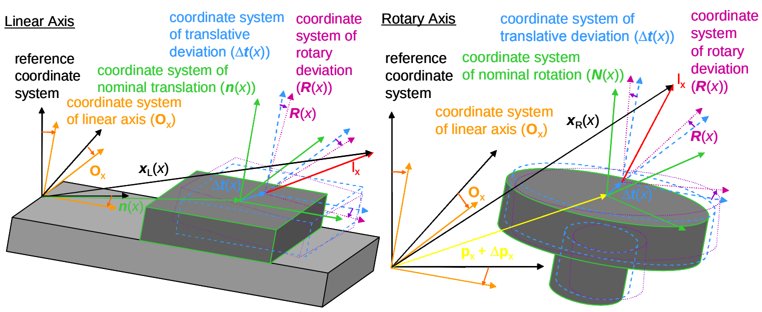

Figure 2: Basic equations for linear (left side) and rotary (right side) axes

For the rotary axis the basic equation is:

$$\boldsymbol{x}_{\mathrm{R}}(x) = \mathbf{O}_{\mathrm{x}}\left(\mathbf{p}_{\mathrm{x}} + \Delta\mathbf{p}_{\mathrm{x}} + \Delta\boldsymbol{t}(x) + \Delta\boldsymbol{R}(x)\cdot\boldsymbol{N}(x)\cdot\mathbf{l}_{\mathrm{x}}\right) \qquad (2)$$

$\mathbf{N}(x)$ represents the nominal axis position (orientation) by a 3x3 matrix. $\mathbf{p}_x$ (3x1 vector) contains the nominal offset of the rotary axis in the reference coordinate system and $\Delta\mathbf{p}_x$ (3x1 vector) the measurable offset deviation. The resulting three-dimensional deviation $\Delta\mathbf{x}(x)$ of the reference point can be calculated by subtracting the nominal position of $\mathbf{l}_x$ from the equation (1) and (2):

$$\Delta\boldsymbol{x}_{\mathrm{L}}(x) = \boldsymbol{x}_{\mathrm{L}}(x) - \left(\boldsymbol{n}(x) + \mathbf{l}_{\mathrm{x}}\right) \quad (3) \qquad \Delta\boldsymbol{x}_{\mathrm{R}}(x) = \boldsymbol{x}_{\mathrm{R}}(x) - \left(\mathbf{p}_{\mathrm{x}} + \boldsymbol{N}(x)\cdot\mathbf{l}_{\mathrm{x}}\right) \quad (4)$$

2.2 Modelling process for multi-axis machines

In each 5-axis machine linear and rotary axes are linked mechanically to a multi-axis system. By means of a simple linking process the basic equations can be combined flexible with each other. Due to the utilization of different coordinate systems and the stacking of the axes, the reference coordinate system of the upper axis and the coordinate system of the rotary deviation of the axis under it can be assumed as identical. This enables to replace the vector $\mathbf{l}_{lower}$ of the lower axis by $\mathbf{x}_{upper}(x)$ of the upper axis. Therewith multi-axis system can be modelled systematically by including the basic equations into each other correspondingly to the axes sequence (axis configuration).
Accordingly to this simple linking process all kinds of 5-axis configuration can be modelled using both basic equations. For example the geometrical machining accuracy of a C-A-Y-X-Z-axis machine (Fig. 3) can be expressed by:

$$\boldsymbol{x}_{real}(x,y,z,a,c) = \mathbf{O}_y\left(\boldsymbol{n}(y)+\Delta\boldsymbol{t}(y)+\Delta\boldsymbol{R}(y)\cdot\mathbf{O}_x\begin{pmatrix}\boldsymbol{n}(x)+\Delta\boldsymbol{t}(x)+\\ \Delta\boldsymbol{R}(x)\cdot\mathbf{O}_z\begin{pmatrix}\boldsymbol{n}(z)+\\ \Delta\boldsymbol{t}(z)+\Delta\boldsymbol{R}(z)\cdot\mathbf{l}_z\end{pmatrix}\end{pmatrix}\right) - \mathbf{O}_a\begin{pmatrix}\mathbf{p}_a+\Delta\mathbf{p}_a+\Delta\boldsymbol{t}(a)+\\ \Delta\boldsymbol{R}(a)\cdot\boldsymbol{N}(a)\cdot\mathbf{O}_c\begin{pmatrix}\mathbf{p}_c+\Delta\mathbf{p}_c+\\ \Delta\boldsymbol{t}(c)+\Delta\boldsymbol{R}(c)\cdot\boldsymbol{N}(c)\cdot\mathbf{l}_c\end{pmatrix}\end{pmatrix} \tag{5}$$

$$\boldsymbol{x}_{target}(x,y,z,a,c) = \left(\boldsymbol{n}(x)+\boldsymbol{n}(y)+\boldsymbol{n}(z)+\mathbf{l}_z-\left(\mathbf{p}_a+\boldsymbol{N}(a)\cdot\left(\mathbf{p}_c+\boldsymbol{N}(c)\cdot\mathbf{l}_c\right)\right)\right) \tag{6}$$

$$\Delta\boldsymbol{x}(x,y,z,a,c) = \boldsymbol{x}(x,y,z,a,c) - \boldsymbol{x}_{target}(x,y,z,a,c) \tag{7}$$

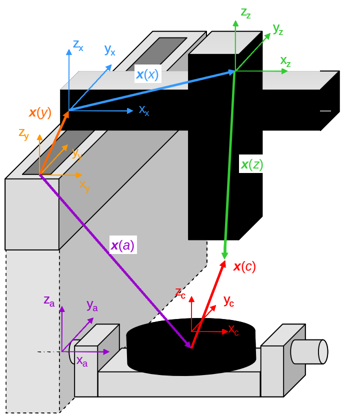

Figure 3: Kinematic chain of a machine tool with C-A-Y-X-Z configuration

$\mathbf{x}_{target}$ describes the nominal vector between work piece and tool (ideal machine without any inaccuracy), whereas $\mathbf{x}_{real}$ describes the real vector due to inaccuracies of the axis system. $\mathbf{l}_z$ represents the tool geometry and $\mathbf{l}_c$ a local position of the work piece.

The mathematical models represent finally the transformation of the single axis errors to the relative 3D deviations of a given tool path in consideration of the axis configuration, the machine size and the tool length. The tool paths represent the nominal relative movements of tool and work piece.

3 Sensitivity analyses of error budgets

To identify inferior and superior errors, within the sensitivity analyses the impacts of each single axis error on the machining accuracy were evaluated systematically independent of their amount and independent of the other axis errors just in consideration of the geometrical machine tool properties like axis lengths and axis configuration.

3.1 Procedure of sensitivity analysis

For the automated performance of the analysis an algorithm was implemented accordingly to figure 4 (left side). The centre of the algorithm is represented by the equations for the 5-axis model (e.g. equation (7)). By inputting information about axis configuration, machine size and tool size the specific machine model will be generated automatically. Furthermore tool paths have to be defined. The paths have to ensure that all 5 axes are involved in the movement and the axis ranges will be pass through as entire as possible. To evaluate the impact of the axis errors separately, only one axis error will be inputted in the model with a constant amount. By means of the model the relative 3D deviation between the target and the real tool paths will be calculated. After that the maximum value of the deviations will be determined and the constant amount will be eliminated from the value so that a dimensionless impact factor results. The impact factor represents the amplification with which the axis error impacts the machining accuracy due to the geometrical properties as well as the axis configuration of the machine. This procedure has to be executed separately for all 42 axis errors.

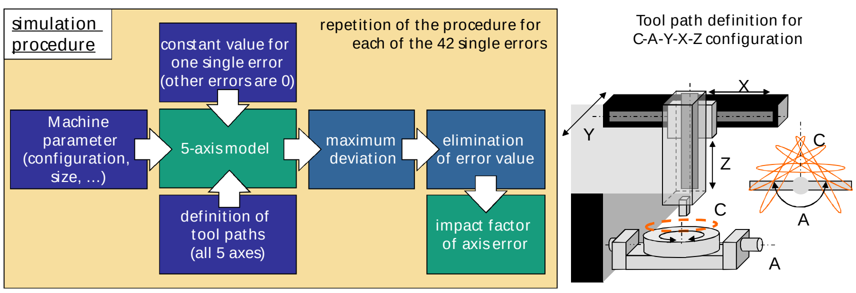

Figure 4: Scheme of the sensitivity analyses simulation procedure (left) and tool path definition (right)

As already mentioned the tool paths have to ensure the involvement of all 5 axes. As example for the impact analyses of a C-A-Y-X-Z machine the following tool paths were used (Fig. 4, right side): A reference point on the work

piece table represents a circle by the rotation of the C-axis. The circle radius and the distance to the work piece table surface describe the work piece dimensions. The X- and Y-axis follow the movement of the reference point by interpolating the circle. To involve the A-axis, stepwise inclined circles around the A-axis will be realised. Consequently all 5 axes are involved in the movement and by an appropriate definition of the circle radius and distance also the entire axis ranges will be considered.
For other axis configurations different tool paths have to be used. However the basic idea of circle movements using the linear and rotary axes can be transferred easily to other machine types.

3.2 Simulation results of sensitivity analyses

Within first simulations a C-A-Y-X-Z machine configuration was simulated that is characterised by a machining volume of 800x800x600 mm³ as well as Y-X-Z-C-A machine configuration with a machining volume of 8000x4000x2000 mm³. To investigate the influence of different work piece sizes, small, medium and large sized work pieces were considered. Figure 5 shows the simulated impact factors of the 42 axis errors.

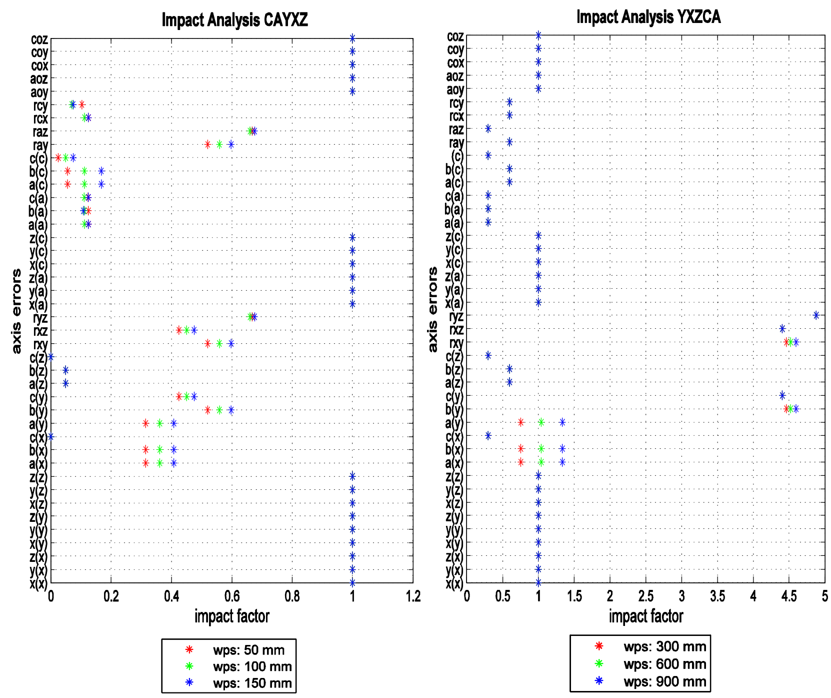

Figure 5: Impact factors of the axis errors of a medium sized C-A-Y-X-Z and Y-X-Z-C-A configuration in consideration of a small (wps: 50 / 300 mm), medium (wps 100 / 600 mm) and large sized work piece (wps 150 / 900 mm)

It can be stated, that translational errors (e.g. straightness) have a constant impact of 1. However the rotational errors (e.g. yawing) have a non-constant impact depending on the work piece size. Furthermore the axis configuration has a strong influence on the amount of the impact factors. To reduce the practical effort for the machine calibration the results indicate that some errors might be neglected because they have an inferior impact with respect to others.

These first results were made for one specific machine size. But it can be assumed that the machine size influences the impact of the rotational axis error due to the geometrical properties. Consequently further simulations were performed in which the machine size was varied systematically. Figure 6 represent the impact factor of the x-axis roll error depending in the machine size and on different work piece sizes. Here the influence of the machine size on the impact factor clearly appears.

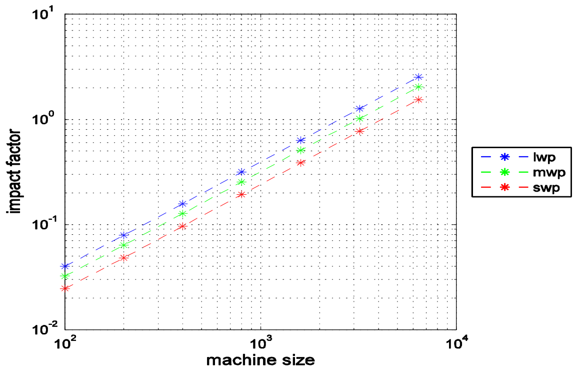

Figure 6: Impact factor of the x-axis roll error depending on the machine size and in consideration of a small (swp), medium (mwp) and large sized work piece (lwp) for a C-A-Y-X-Z configuration

3.3 Impact of sensitivity analyses on metrological 5-axis calibration

The results of the sensitivity analyses demonstrate that the impact of rotational axis errors depends on the machine size, the axis configuration and on the work piece size. Other (here not published) simulations also show that the tool size influences the impact factors. Based on the simulated impact factor characteristics, inferior and superior axis errors can be identified. Due to their inferior impact on the machining accuracy the aim is to neglect the inferior axis errors within metrological machine calibration to reduce the time effort.

However the simulated impact factors only consider the geometrical machine properties and not the real amount of the axis error. Thus a kind of metrological quick check would be very helpful to get information whether an axis error has a small or big amount. The performance of such a quick check in combination with the simulated impact factors will help the operator to decide which axis errors have to be calibrated and compensated.

4 Metrological quick check of 5-axis machine tools

4.1 Metrological procedure

A quick check procedure should consider all 5 axes. This can be realized by inclined circles that require the simultaneous movement of the linear and rotary axes. In consideration of a C-A-Y-X-Z configuration the rotation of the work piece table represents the basis (non-inclined) circle that will be inclined by the A-axis. The linear axes (X, Y, Z) have to follow the circle movements. The circle diameter and its distance to the work piece table determine the involved axes ranges. By the movement of all axes, all 42 axis errors appear. Thus measuring the relative deviation between the both circle movements (A-C, X-Y-Z), all axis errors are represented within the measured data. Consequently metrology systems have to be identified that capacitates the measurement of the circle deviations.
The described metrological procedure equals to the used tool paths and simulations of the impact analyses. Thus the results of the impact analyses can be validated using the quick check metrology procedure.

4.2 Application of metrology

For the practical application of such a quick check different metrology systems are capable [11]. Within first tests the R-Test [12] and the Double-Ball-Bar [1] have been used (Fig. 7). Both systems are well established metrology devices, easily to apply in machine tools and have a measurement uncertainty of 1 µm. The R-Test detects 3D deviations between a single reference ball and a probe head, whereas the Double-Ball-Bar measures 1D deviation between two reference points. Nonetheless the above described test procedure can be performed with both instruments.
The metrology procedure as well as the metrology systems can be applied also in other machine types. However the tool paths have to be adjusted due to different axis kinematics.

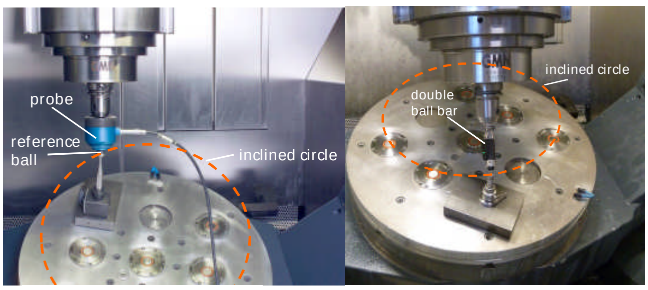

Figure 7: Metrological procedures applying the R-Test (left side) and the Double-Ball-Bar (right side)

4.3 First measurement results

First practical tests have been realized by using the R-Test and the Double-Ball-Bar in a C-A-Y-X-Z configured machine tool. With each metrology system three inclined circles were measured (A = 0°, 30°, -30°). The complete measurement activities (setup and measurements with both systems) took less than 2 hours. Figure 8 represent the test results. The systems show comparable absolute deviations (in consideration of the measurement uncertainty). Consequently both systems provide similar information about the machining accuracy and both seem to be capable for a quick check procedure. Comparing the deviations of the inclined (A = 30°, -30°) and non-inclined (A = 0°) circles, the tests indicate further that for a comprehensive information (worst-case) of the overall machining accuracy all 5 axes should be involved in the measurement process simultaneously.

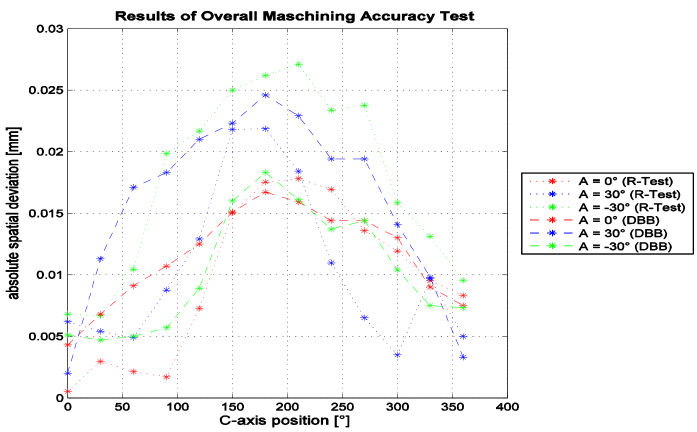

Figure 8: Measurement results of the quick check procedure applying the R-Test and the Double-Ball-Bar (DBB)

The first results show only general deviation information. However the developed mathematical models can be used to estimate the amount of single axis errors quickly by evaluating the measured data. For this the models will be inverted. Then they represent the transformation of measured deviations to single axis errors.

5 Conclusion and Outlook

Impact factors for all axis errors can be calculated systematically for different machine types and sizes. Based on the impact factors superior and inferior errors can be identified. The goal is to neglect the inferior errors within calibration and compensation activities to decrease time efforts. To validate the simulated impact factors and to get information about the real amount of the axes errors an approach for a metrological quick check was presented.

Within further research work the quick check will be used to validate the impact factors metrologically. Furthermore the developed 5-axis models will be used to evaluate the data measured with the quick check in order to clarify whether an axis error is inferior or superior. And finally controller based compensation tests will be performed that focuses on the compensation of only superior errors and that will demonstrate if inferior errors can be neglected.

6 Acknowledgement

The authors would like to thank the German government (BMWi) and the foundation "Otto von Guericke" (AiF) for the financial support of the project 'Opti5AchS' (# 17032N).

References

[1] Schwenke, H. et al. Geometric error measurement and compensation of machines – An update. Annals of the CIRP 57, 2008, page 660-675

[2] Utsch, T. P. Steigerung der Arbeitsgenauigkeit mehrachsiger Maschinensysteme durch Kompakt- und Integralbauweise am Beispiel einer 5-Achs Maschine. Dissertation, RWTH Aachen, 2012

[3] Al-Badrawy, S. J. Fertigungsgenauigkeit von Fünf-Achsen-Fräsmaschinen, Carl Hanser Verlag, München, 1994

[4] Weck, M. Werkzeugmaschinen – Messtechnische Untersuchung und Beurteilung, Berlin Heidelberg New York, Springer-Verlag, 2001

[5] Kahn, A. and Chen, W. A methodology for systematic error compensation in five-axis machine tools. In: The international Journal of Advanced Manufacturing Technology, issue 53, page 615-628, 2011

[6] Knapp, W. et al. Übersichtsvortrag: Geometrieabweichungen von Werkzeugmaschinen. Proceedings of the tutorial Volumetrische Kompensation von Werkzeugmaschinen, Braunschweig, 2009

[7] Srivastava, A. et al. Modelling geometric and thermal errors in a five axis CNC machine tool. In: The international Journal of Advanced Manufacturing Technology, issue 9, page 1321-1337, 1995

[8] Rahman, M. et al. Modelling, measurement and compensation of multi-axis machine tools. Part I: theory. In: International Journal of Machine Tools & Manufacture, issue 40, page 1535-1546, 2000

[9] Schmitt, R. et al. Kinematische Kalibrierung von 5-Achs Werkzeugmaschinen mit LaserTracern. Allgemeine Vermessungs Nachrichten, 2009, issue 6, page 214-219

[10] Jatzkowski, P. Ressourceneffiziente Kalibrierung von 5-Achs Werkzeugmaschinen mit Tracking Interferometern. Dissertation, RWTH Aachen, 2011

[11] Brecher, C. et al. A simple yet comprehensive approach to the testing of machine tools with arbitrary axis configurations. In: Proceedings of 12th International Conference of the euspen, Vol. 1, page 276-279, 2012

[12] Florussen, G. Kalibrierung an Koordinatenmessmaschinen und Präzisionsmaschinen mit kleinem Berarbeitungsraum. Proceedings of the tutorial Praxis der Mikrofertigung, Berlin, 2012