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Compact design for high precision machine tools

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ABSTRACT

Due to raising functional integration in micro fluidic, micro mechanic, micro electronic and micro optical systems the trend to scaling down the work piece sizes while increasing its complexity requires high precise machine accuracy. With respect to the process and geometrical parameters, most of the finishing manufacturing processes can be covered by milling and grinding operations with three or five machine axes. But whereas the available machine tools hardly achieve the required process dynamic and accuracy in all degrees of freedom, the requirements still increase. For this reason the Fraunhofer IPT has developed high precise machine tools following a compact design strategy by reducing the overall machine dimensions as far as conventional machine components such as measuring or drive systems were available. The developments of two compact machine tools exemplify the dynamic and accuracy enhancement by compact design and are described in the following.

1. Introduction

The requirements for the manufacturing of high-precise complex micro parts cannot be satisfied alone by conventional machine systems since they are limited in their accuracy or stiffness on the one hand or limited in their dynamic on the other hand [1,2]. Fundamentals for the designing of precision and ultra-precision machine tools [3,4] have been discussed extensively. Related to the five-axes machine accuracy challenge especially the error and the bearing reaction amplifying cantilevers as well as their ratio to each other and their common balancing within the overall machine error budget have been pointed out as significant research areas for the designing of high and ultra-precision machine tools.

Whereas the Abbe Principle (first order) describes the translatory measuring error caused by axes tilting and a distance to the solid measure [5], the Pivot Error is caused by the inevitable distance in-between process contact point and the pivot line of a rotary axis, which amplifies the rotary measuring error. The Steiner Distance is here defined as the distance of the gravity centre point to the pivot line in rotary axes and to the point of acceleration force incidence in linear axes, respectively. The thermal error [6] is taken into account for homogenous temperature distribution causing linear and rotary errors by thermal growth.

All relevant error influences are described in the machine error budget [7]. For the present kinematic considerations a homogenous transformation matrix form [8] is developed. Formula 1 exemplifies the rotation and the translation of the x-axis related coordinate system σ_x. Both, the work piece and the tool system are described by the matrix multiplication of each sub-coordinate system matrix with cantilever matrices L, which contains the straightness error, and feed matrices T (formula 2, 3). The overall machine error ε (formula 4) is described by the difference of the work piece matrix X_{WP} and the tool centre point matrix X_{TCP}, whereas matrix A is defined as 3×4 unit matrix and B as 4×1 unit vector (fourth), only for realising the mathematical operation for achieving the 3D error vector.

$$\sigma_x = \begin{pmatrix} 1 & -\delta\varphi_z(x) & \delta\varphi_y(x) & \delta x(x) \\ \delta\varphi_z(x) & 1 & -\delta\varphi_x(x) & \delta y(x) \\ -\delta\varphi_y(x) & \delta\varphi_x(x) & 1 & \delta z(x) \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1}$$

$$X_{TCP} = L_z^0 T_z \sigma_z L_{TCP}^z \tag{2}$$

$$X_{WP} = L_x^0 T_x \sigma_x L_y^x T_y \sigma_y L_{WP}^c \tag{3}$$

$$\vec{\varepsilon} = (AX_{WP}B) - (AX_{TCP}B) - \vec{x}_{rel,set} \tag{4}$$

The compact design means the alignment of high-precision functional items such as torque drive, bearing and measuring system in smallest space. The described machine error budget provides an overview of the impact of the particular precision design fundamentals, that have been deployed consequently by following the compact design strategy. This is exemplified by the calculation of a linear slide error in one direction, caused by the linear positioning error (including Abbe error), the geometrical

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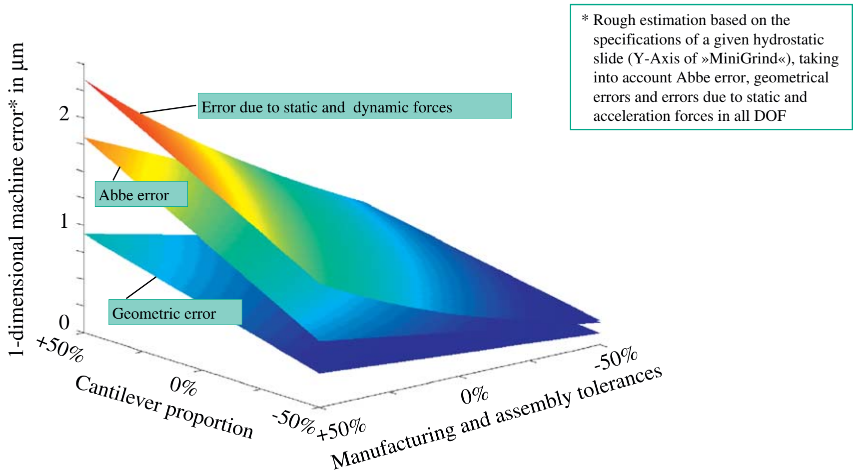

Fig. 1. Impact of the component sizes and the manufacturing/assembly tolerances on the machine error.

errors and the static as well as acceleration forces induced deviations: As shown in Fig. 1, the scaling down of the component sizes (cantilever proportion −50%) has a significant higher impact on the machine accuracy as the manufacturing and assembly tolerances. Using the two together, highest working accuracy can be achieved.

Due to compact conventional, not miniaturised functional items, the resulting machine systems can provide both, high accuracy and high stiffness. The benefit of this design strategy is the reduction of the error activating cantilevers and therewith the decrease of the Abbe error, the Pivot error (in rotary axis), the Steiner distance as well as the thermal error by simply reducing the overall machine size. The accuracy enhancement by error activating cantilever reduction is additionally realised by decrementing the sum of items and joint patches in the force flux by functional integration [1]. Latter is named "integral design" and can be seen as a second stage optimisation of compact design. The compact design deployment is exemplified by the development of a three-axis milling machine and a five-axis grinding machine in the following.

2. High precision impulse decoupled compact milling machine—MiniMill

2.1. Requirements on high-dynamic three-axis micro milling

The design of the compact milling machine is primarily influenced by the product range and the process demands of the micro milling process. More than 90% of the work pieces can be covered in a travel range of $200 \times 200 \times 100\ \text{mm}^3$ in the field of micro milling [9]. Looking at the specifications of geometries and complex structure details like micro fluidic channels or free-form surfaces milling tools down to 300 µm and less are needed for the manufacturing process. Process analysis have shown that best cutting performance focusing on tool wear and surface quality can be reached at cutting speeds of 140 m/min and a infeed of 3 µm/revolution [10]. Unlike conventional machining these process requirements call for extreme dynamics to keep the path speed constant at complex surfaces. Path speeds of up to 1.500 mm/min are needed to operate in an optimised process latitude which demands very high and equal acceleration performance of all axes and especially jerk [2]. The biggest impact on a constant path speed at a micro milling process is the resistance of the machine design against jerk, to allow as much jerk as possible from the control side. To increase that jerk resistance and based on these afore given demands linear direct drives have been chosen and combined with impulse decoupling systems to be integrated into the MiniMill machine to minimise the impact on the structure.

2.2. Machine design

To achieve highest accuracies, different arrangement of axes have been analysed under the consideration of the chosen impulse decoupling system and the process requirements. Due to the design of a three-axis machine, at least two axes have to be stacked either on the tool or on the work piece side. Examining conventional high precision machine tools, the slowest axis is the vertical *z*-axis, which is normally equipped with a self-locking lead screw.

To provide the same dynamics of up to 3 g in all three axes the *z*-axis is mounted separately on the tool side. Passive magnetic actors are integrated in the *z*-axis as weight compensation to supply the same acceleration in positive and negative *z*-direction. The impulse decoupled horizontal *x*- and *y*-axis are stacked and integrated in a compact and lightweight cross table design. To minimise Abbe errors the drives and guidance systems integrated into the cross table have to be arranged as close as possible. As the application of this machine tool is the milling of non-optical moulds the integration of ball bearings is allowing for a very compact design.

Fig. 2 presents the overall design of the compact miniature with an integrated impulse decoupled cross table. To minimise the weight of the moved mass different direct drives have been analysed and an iron core motor was chosen to be integrated in the *x*-axis. Especially the motor characteristics of a high continuous force at low weight is necessary to accept the process force and additionally provide enough maximum force to assure high accelerations and jerks even in process. This offers some important advantages, compared to an ironless drive in the upper axis. The total weight iron core drives (coil incl. magnet track) is lower than ironless drives because only one magnet track is needed. Compared to ironless motors the slim configuration allows for a compact design and minimised vertical distances between the *x*- and *y*-axis guidance, helping to minimise stacking errors. Another advantage is the integrated precision cooling unit to keep heat away from the structure.

Keeping the stacked weight on the carrying *y*-axis low, the mass of the damping slide is only slightly higher than the *x*-axis slide.