Investigations on kinematic couplings for tool-changing interfaces in highest-precision devices

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Abstract

Highest precision devices are used to measure, manipulate and structure objects with a resolution down to the nanometre range. Manufacturing processes in particular are creating the demand for a highly reproducible tool changing system. The design needs to be free of overconstraints, vacuum compatible and long-term stable. Especially the demand for vacuum compatibility represents a challenge due to friction conditions, which affect the reproducibility. The tool centre point needs to be located very precisely at a defined position in the device. In case of a Cartesian device layout, the position is represented by the virtual intersection of the three linear measuring axes. Manufacturing and assembly tolerances require the adjustment of the tool centre point. Because of the limited space, the adjustment needs to be integrated into the changing system. The usage of various tools requires an individual adjustment at the side of the tool. For this purpose, new arrangements of kinematic couplings are investigated. Neither analytical nor numerical models are sufficient to prove the fulfillment of the requirements. Therefore, a setup was developed to measure the reproducibility in five DOF. The metrological properties of the measuring setup were proven by means of a three-dimensional vector-based uncertainty analysis. By using this measuring setup, different arrangements of the coupling points, the influence of the geometry and the material of the coupling members as well as the influence of the adjustment on the reproducibility and long-term stability are investigated with nanometre uncertainty.

Keywords: kinematic couplings, adjustable kinematic couplings, tool changing interfaces, high-precision measuring, nanofabrication

1. Introduction

The further development of nanofabrication machines requires enhancements of the reproducibility of tool-changing systems under vacuum conditions. Due to the positioning uncertainty of the machines of about 30 nm, the reproducibility of the tool centre point must be of the same order of magnitude. Currently used kinematic couplings suffer by friction and thus do not meet these requirements [1, 2].

This work deals with the investigation of highly reproducible kinematic couplings for an application in vacuum with relatively low loads. A functional extension of the kinematic coupling by an adjustment is considered. Based on a developed measurement setup with a measurement uncertainty in the nanometre range, the achievable reproducibility can be verified.

2. Measuring setup for the investigation of the reproducibility

A reliable calculation of the targeted reproducibility of the position is neither possible with numerical nor analytical methods. This is due to the fact that the reproducibility in the desired range is mainly influenced by friction and stick-slip effects of an random character, which is even enhanced by the vacuum environment. Influences on the reproducibility due to changing loads are not considered here. Therefore, a measurement setup was developed, which allows the reproducibility to be measured in the required five DOF. Rotations around the tool axis are negligible for the tools used in the nanofabrication machine.

2.1. Measuring concept

In order to develop a measurement concept, 21 potential measurement devices were systematically listed, compared and a pre-selection was made. Based on this pre-selection, a number of 13 technical principles out of up to two measurement devices were created and evaluated. The solution based on five single-electrode capacitive sensors showed the best technical conformity. These sensors enable absolute measurements with a resolution of 0.5 nm, short closed metrological loops and a minimal installation space. Three z-sensors are used to measure the position in z-direction and the rotations around the x- and y-axis. Two further sensors are used to measure the position in x- and y-direction. All sensors are operated in static and integrating measurement mode. The measuring setup is arranged in the way that the coupling is only loaded by the weight force. After the measurement is completed, the two coupling halves are separated and reconnected by a lifting device. This device has no contact with the moving coupling part during the measurement. After connecting the two coupling halves, a sufficient settling time is waited for before the next measurement is started.

2.2 Measurement uncertainty analysis

A three-dimensional, vector-based measurement uncertainty analysis was performed to qualify the selected principle as a sound foundation for the following design [3]. For this purpose, two closed vector courses were created in which each influence is modelled as a single vector. The vector \( x_o \) (see formula 1) corresponds to the minimum and vector \( x_s \) (equivalent to \( x_0 \)) to the maximum expected reproducibility of 5 \( \mu \)m and 10 \( \mu \)rad. The
measurement uncertainty of the setup is equivalent to the uncertainty of the difference between the two vector contours (see formula 2).

\[
\begin{align*}
\vec{x}_A &= \vec{x}_{MAX} + \vec{x}_x + \vec{x}_{KAP} + \vec{x}_{AB} + \vec{x}_\cos + \sum_{i=1}^{11} \vec{x}_{FRi} \\
\vec{u}(\vec{x}_{MAX}) &= \vec{u}(\vec{x}_A - \vec{x}_B)
\end{align*}
\]

Considered influences are thermal strains of the moving coupling half ($x_{n}o$), the frame components ($x_{n}$) and the sensors ($x_n$), the measurement uncertainty of the sensors ($x_{\text{sensor}}$), first and second order Abbe errors ($x_{\text{Abbe}}$) and cosine errors ($x_{\cos}$). As a result an expanded measurement uncertainty according to the “Guide to the expression of uncertainty in measurement” (GUM) of approximately 9 nm in every coordinate direction and 5.3 nrad for rotations can be attained. Therefore, the environment of the measurement setup must provide a temperature stabilization of ± 0.05 K because thermal influences predominate the translational measurement uncertainty. A further prerequisite is an initial precise measurement of the position of the sensors with an uncertainty of 1 µm. This could be done with a coordinate measurement machine. Thus, measurement uncertainties caused by position and angle deviations of the sensors can be corrected mathematically.

2.3. Design of the measuring setup

To minimize thermal and disturbing mechanical effects, all five sensors are fixed on a monolithic frame made of Zerodur® (8) as shown in figure 1. This material is characterized by a thermal expansion of $(0 \pm 0.1 \times 10^{-6}) / K$ and a Young's modulus of 90,3 GPa that is comparatively high for glass ceramics [4]. The cylindrical sensors (3, 6) are mounted in v-grooves for a defined and reproducible position. Due to the working distance of the sensors of 50 µm, an adjustment performed by means of a feeler gauge is needed. The sensors are fixed by a small but sufficient clamping force. The top plate is also made of Zerodur® (7) and separately grounded capacitor plates are attached (5) as required measuring surface for the sensors. The kinematic couplings are integrated into the measuring setup in form of interchangeable inserts (1). This allows the variation of materials, shapes, and dimensions. Due to these variations, spacer elements (2) are necessary to keep the measuring surface (5) of the x and y sensors (6) in the same z-position.

![Figure 1. measuring setup: (1) interchangeable inserts; (2) spacer elements; (3) z-sensor in v-groove; (4) preparation for alternative arrangements; (5) capacitor measuring plate; (6) x, y-sensor in v-groove; (7) top plate; (8) metrological frame](image)

A lifting device is needed for repeated automated measurement. During the lifting process, neither a translational nor a rotational guide deviation should lead to a collision with the sensors. For this purpose, a double membrane spring guide (3) is used (see figure 2). The guide is characterized by very small guidance deviations and a high stiffness against tilting due to the double spring design. The connection to the top plate of the coupling (5, 6) during the lifting process is made by three ball-plane contacts. It is detachable by a rotation around the z-axis (4) for assembly and disassembly of the lifting device. In addition, the guiding axis must be adjusted in two independent angular motions relatively to the coupling axis (2). The upper adjustment table is connected to the frame (not shown). The actuation of the lifting device is done by use of a voice coil, which is placed at the largest possible distance from the measuring points connected by a flexible element to minimize impacts due to overconstrains (1). All components of the lifting device are designed for use in vacuum.

![Figure 2. lift of device based on a diaphragm spring guide for an automated measurement in vacuum](image)

3. Design of the kinematic coupling

The kinematic couplings themselves are initially designed as Kelvin or Maxwell clamps. An additional position for sensor and coupling element was designed to investigate the arrangement of the coupling points at the tips of a rectangular triangle (see (4) in figure 1). This arrangement is promising for the intended extension of the kinematic coupling by an adjustment. Due to the small space available, this has to be integrated directly into the kinematic coupling and an independent adjustment of individual DOF is required.

4. Conclusion

In summary, kinematic couplings show good suitability for use as tool changing interfaces in nanofabrication machines. The achievable reproducibility can be proven under vacuum conditions by a developed, standalone measurement setup. A detailed measurement uncertainty analysis was performed to prove a nanometre uncertainty. The kinematic coupling is implemented using interchangeable inserts, which enables investigations on materials, shapes and dimensions.

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References