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Investigations on low-friction kinematic couplings based on compliant mechanisms

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Abstract
New demands concerning nanofabrication require the extension of the nanomeasuring machines developed at the Technische Universität Ilmenau by a highly reproducible tool changing system. Conventional kinematic couplings consisting of three equally distributed ball-V-groove pairings are prone to sliding friction effects close to the final position. This paper presents the development of a kinematic coupling with a self-centring V-groove realized using a compliant mechanism. Sliding movements and stick-slip effects are reduced to a minimum to enhance the reproducibility and avoid material abrasion and debris. For this purpose, planar mechanisms with concentrated compliances were developed and optimized concerning design space, straightness of the guiding path, and manufacturability. Unavoidable randomized small stick-slip effects, result in deviations to the intended linear movement thus having a direct influence on the reproducibility of the whole kinematic coupling. Ten different planar mechanisms have been developed and evaluated. In addition to the mentioned optimization criteria, also the simplicity of the mechanisms was evaluated. A parallel crank, a double Roberts mechanism, and a pendulum mechanism proved to be the best solutions. Due to the static force given by the preload, the parallel mechanism is preferred since it can be designed in a way that all hinges are loaded by tension only. An optimization of the hinge contour in terms of low stiffness and low rotational axis deviations was carried out. Subsequently, the mechanical properties of the mechanism were investigated with an FE analysis.

Keywords: kinematic coupling, nanofabrication, tool changing system, compliant mechanism, flexure hinges

1. Introduction

With ongoing research on nanomeasuring machines developed at Technische Universität Ilmenau and advances in the field of nanofabrication, the need for a highly reproducible tool changing system arises [1, 2]. This tool changing system is based on a statically determined kinematic coupling. The targeted reproducibility of the tool centre point, whose distance from the coupling is in the order of 50 mm, is below 50 nm which is an improvement of one order compared to the state of the art. The reproducibility of conventional kinematic couplings consisting of three equally distributed ball-V-groove pairings suffers due to sliding friction at the closing final position. This effect occurs more intensively under vacuum conditions. To minimize these friction effects, to avoid any material abrasion, and to enhance reproducibility, a compliant mechanism is integrated into each V-groove half. This mechanism needs to be arranged in a way, to allow self-centring of the V-groove.

2. State of the art

The application of self-centring ball-V-groove pairings is frequently indicated in the state of the art of kinematic couplings. A typical example shows a rotatory mechanism with 1 DOF presented in [3], another one is based on a 2 DOF mechanism with distributed compliances [4]. These and other mechanisms found in a systematic survey do not meet the demands on reproducibility, needed for the application in the nanofabrication machine. To increase the reproducibility significantly, assumptions taken in the literature, like ideal geometries of the pairing surfaces and simplified friction models, are no longer applicable.

3. Development of a mechanism

The aim of this work is the development of a Maxwell clamp with self-centring V-grooves that ideally completely avoids sliding movements as shown in figure 1. The design space is taken from the measurement setup for the determination of the reproducibility presented in [2]. The influence of unavoidable randomized small stick-slip effects is neglected in the first approach. An investigation on the direction and value of possible motions during the coupling process revealed that a movement in the negative y-direction is crucial since the reproducibility of the tool centre point is mainly influenced by angular deviations of the kinematic coupling. A free movement in the x-y plane would be advantageous but was not yet investigated. Since only the approaching part of the movement is crucial for the reproducibility, the required movement range is below 0.1 mm. The stiffness of the mechanism needs to be optimized to allow evasive motion in the y-direction under the given load of 20 N while having high stiffness in the z-direction. The mechanism developed is based on concentrated compliances.

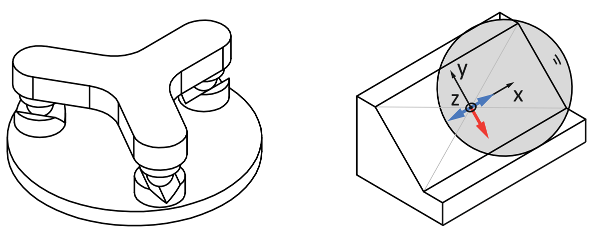

Figure 1. (a) Kinematic coupling as Kelvin clamp; (b) V-groove-half with the ball: necessary movement (red), optional movement (blue).

Research on deployable mechanisms was conducted regarding criteria such as symmetry, planar motion, linear guidance, the absence of crossed links, and the degree of freedom. A number of ten mechanisms were found, each optimized concerning the character of the pathway within a defined design space. These mechanisms are evaluated based on quantified criteria.

3.1. Evaluation criteria

The first criterion is the design space of the planar mechanism due to the very limited design space of the kinematic coupling in the nanofabrication machine. Mechanisms are grouped into 1 DOF mechanisms, mechanisms that can be easily extended for 2 DOF, and mechanisms with 2 DOF. The complexity is described by the number of overall hinges. To consider manufacturability, the cutting length of the mechanism in a monolithic design was examined. Stiffness in negative z-direction was calculated and taken into account, as well as systematic error motion in the z-direction, given by the individual kinematics. All evaluation criteria are given an additional weighting, whereby criteria complexity, stiffness, and error motion in the z-direction are weighted most strongly.

3.2. Results of the evaluation

As a result of the evaluation, the three mechanisms shown in figure 2 were considered for further investigations.

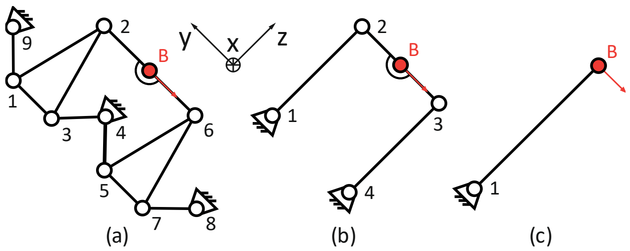

Figure 2. Most promising mechanisms with the ball located at point B: (a) double Roberts mechanism, (b) parallel crank, (c) pendulum mechanism

The double Roberts mechanism consists of 9 hinges, which makes the manufacturing of the mechanism within the given design space difficult. Further, hinges 2 and 6 are loaded by compression, which is problematic when using compliant hinges. The simple pendulum mechanism can be loaded by tension with the right hinge orientation. Due to the simple shape of the mechanism, a rotatory movement is performed which could affect the reproducibility more than a translatory movement. The parallel crank mechanism has two advantages, it shows a linear movement with only a small error movement in negative z-direction, further on all hinges can be loaded by tension in the appropriate arrangement. For these reasons, the parallel crank was selected for the following design process of the mechanism.

4. Design of the mechanism

The selected mechanism is transformed from a rigid-body model to a compliant mechanism. The hinges and the mechanism are arranged in such a way that the preload force loads all the hinges in tension only. In the design of the mechanism, the hinge contour is one of the most important design factors, as it has a strong influence on the overall stiffness and the character and the maximum range of the moving path.
The hinge contour can be optimized between the two limits semicircular and rectangular contour in form of polynomial contours. Therefore, software detasFLEX is used [5]. As result, a semi-circle contour with a minimal hinge height of 0.1 mm is chosen as a good compromise between low stiffness in the y-direction and simple manufacturing.
The final mechanism is shown in figure 3. The outer dimensions of this mechanism are 15.5 mm x 16 mm x 5 mm which fits in the given design space. To ensure the required properties of the mechanism, an FE analysis was subsequently carried out. The stiffness of the mechanism results in c_z= 8.5e-4 N/µm and thus sufficiently small for the mechanism to be deflected by the friction force in the contact, resulting from the preload force. In x- and z-direction the stiffnesses are about three orders higher with c_x = 0.29 N/µm and c_y = 3.15 N/µm. The maximum error motion in the negative z-direction is 591 nm at the contact point at the maximum deflection of 0.1 mm. Since the deflection of the mechanism in z varies only with very small changes of the friction force over the coupling cycles, the influences on the reproducibility are expected to be negligible.

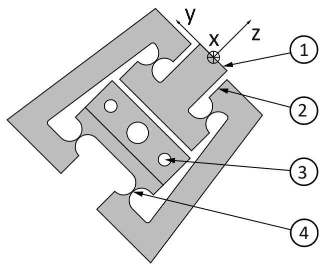

Figure 3. Final mechanism for one V-groove half: (1) ball contact area, (2) end stops, (3) holes for alignment and fixation on to the mount, (4) concentrated compliance in circular shapes

5. Conclusion and outlook

A mechanism with straight-line guidance was developed for the use in the V-groove halves of a kinematic coupling to minimize friction movements and thus improve the reproducibility in comparison to a conventional kinematic coupling. This is especially achieved through the specific optimization of the straight-line guidance, low stiffness in the y-direction, and high stiffness in the negative z-direction. In the next steps, the V-grooves with the developed mechanism will be manufactured, assembled, and tested. More complex mechanisms allowing a free movement in the x-y-plane will be investigated.

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