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Ultra-precise linear motion generated by means of compliant mechanisms

Philipp Gräser[1], Sebastian Linß[2], Lena Zentner[2], René Theska[1]

[1]Precision Engineering Group, Department of Mechanical Engineering, Technische Universität Ilmenau, Germany
[2]Mechanism Technology Group, Department of Mechanical Engineering, Technische Universität Ilmenau, Germany

philipp.graeser@tu-ilmenau.de

Abstract
This article describes a measurement setup for experimental analysis of the path of motion of compliant linkage mechanisms. Especially mechanisms with an ultra-precise linear motion of one coupler point are considered. For a maximum in precision of measurement, interferometric length measure systems are used. In the evaluation of measurement the results of the experimental setup are compared to the results of the simulated path of motion. In this way the simulation model can be refined, thus giving a better description of the kinematic behavior.

Keywords: compliant mechanism, linear motion, flexure hinge, measurement

1. Introduction

Compliant guiding mechanisms with flexure hinges are an alternative to conventional linear guides. Since they show no friction, no wear and no need for maintenance or lubrication they are superior for the unconditional use under vacuum conditions. There is a growing need for those ultra-precision mechanisms, e.g. in the semi-conductor industry and in space applications. New approaches for the optimization of compliant mechanisms have been developed [1]. They allow the definition of the exact path of motion of the end effector in dependence to geometric parameters of the flexure hinges. Prototype based measurements are deployed to evaluate and optimize the precision of the simulated mechanism.

2. Compliant mechanism for linear motion

The function of compliant linkage mechanisms is to transform an input motion to an output motion at an end effector. This transformation can be in form of a change in the direction or the magnitude of the motion path. By the transformation of motion it is possible to change a rotation into a translation and vice versa. In many cases the precision of the path of the end effector is very important. Various mechanisms can be designed for these applications. Fundamental investigations are done based on a simplified mechanism (1:1 transmission ratio) to avoid parasitic side effects.

There are different ways to design a compliant mechanism. One way is to take the rigid-body model (e.g. Fig. 1a), thus concentrating on the design of joints that are most influential. These joints were included to the compliant mechanism in the form of flexure hinges with concentrated compliance. The position and the form of these hinges are defining the function of the whole mechanism. Investigations to the contour have shown that a compromise between a high motion range and a precise path of motion is given by a contour in form of a 4th order polynomial. For comparison two other contours have been investigated: circular and corner-filleted form.

The developed simulation model (Fig. 1b), can be deployed for optimization by variation of the parameters of the flexure hinges to realize a path deviation of some micro meters. For the evaluation it is interesting to know, how a manufactured mechanism works and how precise is the path of motion. To measure this path, a special test bench has been designed.

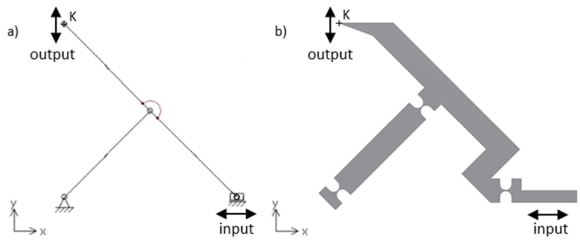

Figure 1. Isosceles centric slider-crank mechanism for a precise linear motion for the coupler point (K):
a) rigid-body mechanism,
b) compliant linkage mechanism

3. Setup for measurement of the output motion path

The basis of the measurement is an interferometric length measurement. With the help of three measured lengths, three parameters for the motion of the mechanism are given.

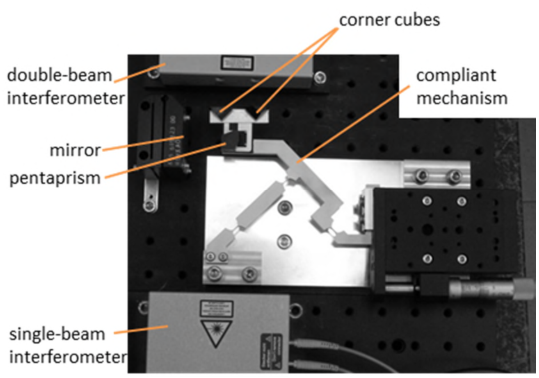

Figure 2. Test bench for measurement of the path of motion of the coupler point K

The parameters are the path difference in *x*- and *y*-direction and the angle $\Delta\phi$ of the end effector. So the path of motion of the coupler point can be described. The test bench for this measurement is shown in Figure 2.

To measure two of the three lengths a double-beam interferometer is used. Instead of a conventional plane mirror, two retro-reflectors in form of corner cubes are used. This is necessary to avoid influences by changes in angle $\Delta\phi$ of the end effector. The two signals y_{m1}, y_{m2} from the double-beam interferometer and the exactly known distance *s* between the two beams enable the calculation of the angle $\Delta\phi$ (eq. 3.1).

$$\Delta\phi = \arctan\left(\frac{y_{m2}-y_{m1}}{s}\right) \qquad (3.1)$$

Additionally one of the two signals (y_{m1}, y_{m2}) represents the path of motion in *y*-direction Δy of the coupler point. This is only given, when the corresponding corner cube is placed in a straight line, which is parallel to the interferometer beam and includes the coupler point K.

With the single-beam interferometer a signal x_m is measured. This signal represents the summation of the distances of motion in *x*- and *y*-direction. To measure this signal the beam from the interferometer is deflected by a pentaprism, thus being invariant to the rotations of the prism. Next to prism the beam is directed to a plane mirror and retraces on the same way. With the length difference Δy, the unknown length difference Δx can be simple calculated (eq. 3.2).

$$\Delta x = x_m - \Delta y \qquad (3.2)$$

The value Δx represents the lateral deviation to the intended precise linear motion. With this test bench the path of motion can be measured with a precision of 0.1 µm.

4. Measurement results and comparison with simulation

With the described test bench three mechanisms with different contour forms were measured. While the basic form of the mechanism was unchanged only the contour of the flexure hinges was varied. This has an influence on the path and range of motion and the stiffness of compliant mechanisms [2]. All the mechanisms are manufactured based on simulation and the optimization of the path of motion with a FEM-model.

The material of the mechanisms is a special aluminium alloy (AlZn5.5MgCu) with a high Young´s modulus. They are manufactured by wire EDM. The material and the manufacturing process have also an influence, which will be investigated too.

The results of the measurement have been compared with these from the simulation; an example is shown in Figure 3. The paths of motion are analysed in the simulated model and on the manufactured mechanisms. All three values from the measurement (Δx, Δy, $\Delta\phi$) are used to evaluate the simulation model. This is necessary to analysed the whole motion of the end effector. This is offered the characterisation of the exactly output motion.

The comparison shows that the simulation and the real motion are matching with a maximum difference in a range of ± 10 µm. The causes for this difference (e.g. type of manufacture, clamping conditions) are currently not covered by simulation model and will be investigated next.

5. Conclusion and outlook

The investigations show that a manufactured compliant linkage mechanism, which is optimized with a simulation model, can be used to realize ultra-precise linear motion. There are many different factors, which have an influence on the precision of the mechanism and its operational capability. Some of these can be considered in the simulation other ones must be investigated based on measurements taken at the manufactured mechanism. Special investigations for a characterization of the deviations will show the differences between two important groups. On one hand the parameters which can be included in the simulation model and on the other deviations given by the limits of the manufacturing accuracy. Experimental investigations on the path of motion of compliant linkage mechanisms are substantial for the optimization of simulation models and a determined syntheses and construction of these mechanisms. Results derived with simple mechanisms will be transferred to more complex models in ongoing research activities.

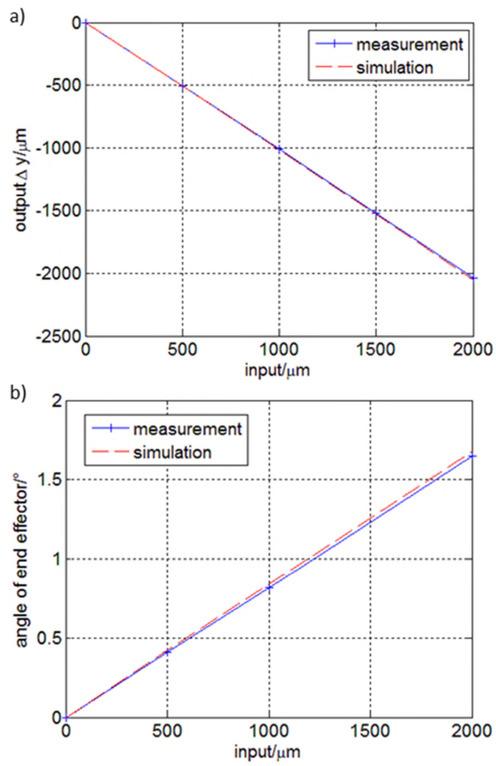

Figure 3. Comparison between the measured and the simulated results
a) for the output motion in *y*-direction Δy
b) for the angle of the end effector $\Delta\phi$

In the future the use of compliant mechanisms will gain in importance, because of their advantages and the possibility to generate exact long travel paths of motion with deviations of some nanometres and arc-seconds or less. To achieve this progress it is necessary to formulate a general approach for the design of compliant linkage mechanisms. This opens new ways to an improvement of the precision of measuring instruments and Ultra Precision Machines.

Acknowledgments

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