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Large stroke ultra-precision planar stage based on compliant mechanisms with polynomial flexure hinge design

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Abstract
Precision stages based on compliant mechanisms have many advantages over conventional linear guides. Therefore they are widely used in many applications in precision engineering, measurement technology, semiconductor industry and space technology. The motion range of high-precise compliant mechanisms is often limited to some micrometres up to submillimetre. This contribution presents the development in the design of a compliant mechanism allowing a bidirectional planar motion with a large stroke of up to 10 mm and a straight line deviation of only a few micrometres. Based on the outstanding reproducibility of the path of motion, positioning and measurement of large objects with accuracy in the nanometre range have been realised.

Keywords: compliant mechanism, straight line guiding, planar stage, flexure hinge, polynomial contour, large stroke of motion

1. Introduction

Compliant mechanisms show several advantages over rigid-body mechanisms since they use flexure hinges instead of conventional hinges. Nevertheless, flexure hinges have a limited rotation angle defined by the limits of the allowed material strain. This is the root cause for the often limited stroke of compliant mechanisms.

This paper presents a monolithic planar stage build from two compliant mechanisms combining ultra-high precision and large stroke of motion (± 10 mm). Each of the mechanisms realises a straight line motion with a deviation less than 2 µm. To derive such a system a structured synthesis for the compliant mechanisms is done. In a first step a rigid-body model is synthesised and scaled with regard to motion and construction parameters (straight line deviation, construction space, etc.). On the basis of this rigid-body model a compliant mechanism is designed by replacing the idealized hinges by flexure hinges with a specific polynomial contour. The two mechanisms are combined orthogonally to one planar stage and transferred to a CAD model as the base for numeric simulations. To verify the FEM simulation results a prototype is manufactured and measured in a test bench.

2. Rigid-body model of the mechanism for one linear motion

The presented planar stage is a combination of two compliant mechanisms based on the same rigid-body model. For the rigid-body model different mechanisms are investigated and compared with respect to parameters of motion and design. After determining the maximum relative rotation angle in all hinges, each model is scaled by the stroke of motion and optimised to reach a minimised straight line deviation for the requested stroke. Also there are some boundary conditions which result from the properties of a compliant mechanism (space between the hinges, maximum angle of each hinge, etc.). The different models are compared regarding their complexity, construction space, trajectory deviations, and number of hinges. The best combination of parameters of the investigated rigid-body models is chosen.

The presented rigid-body mechanism is based on a double parallel crank mechanism with an additional link (L) to reduce the degree of freedom to one. The result is a ten-hinge-mechanism which realises exact linear guiding of the coupler (C), see figure 1.

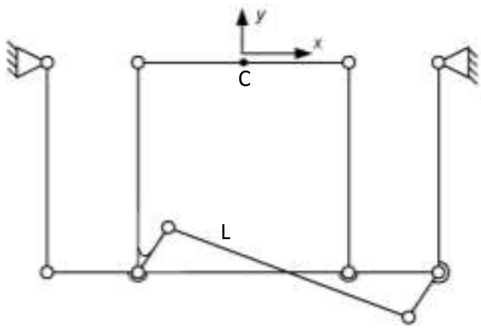

Figure 1. Rigid-body model of the developed ten-hinge-mechanism for a linear motion of the coupler (C) in *x* direction in form of a double parallel crank mechanism with an additional link (L)

3. Simulation model of the planar stage

After the investigation and optimisation of the rigid-body model a compliant mechanism is designed. Therefore, a serial mechanism arrangement is used. The first mechanism for the *x* direction is fixed to the frame. The second mechanism for the *y* direction is orthogonally orientated to the first and fixed at the output link of the first. The output of the second mechanism represents the output of the planar stage, see figure 2. To allow the intended serial planar combination of two mechanisms the first mechanism needs to be increased in size and strength.

For the compliant design of the planar stage all hinges of the rigid-body model are replaced by flexure hinges while keeping the rotation axes of the flexure hinges in the initial state at the same position. During the motion the rotation axes of the flexure hinges change their position. This results in deviations of the rigid-body mechanism and the simulation model. To reduce these deviations and the maximum strain in the flexure hinges, special 4th-order polynomial contours are used. This choice is based on design graphs [1] due to an overall maximum relative rotation angle of 4.6° in the mechanism.

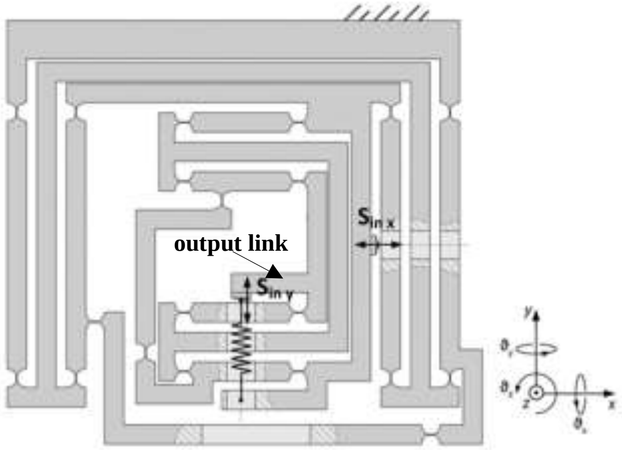

Figure 2. CAD model of the compliant planar stage with two ten-hinge-mechanisms for a linear motion in *x* and *y* direction (all hinges are designed with 4th-order polynomial contour)

4. Measurement of the planar stage prototype

To verify the results of the simulation model a prototype of the planar stage is manufactured and the motion of the output link of the planar stage is measured. The prototype is manufactured from the same aluminium alloy as used in the simulation (EN AW 7075) by wire EDM. The input motion is realised by two linear actuators in form of high-precision DC motors with a resolution of 0.1 µm. With the help of two springs for each actuator there is a symmetric force between the mechanism and the actuator. According to this a force closure between the actuator and the surface of the mechanism is realised in each position. To minimise the friction between the outputs of the actuators and the mechanism there are ball transfer units to transmit the motion.

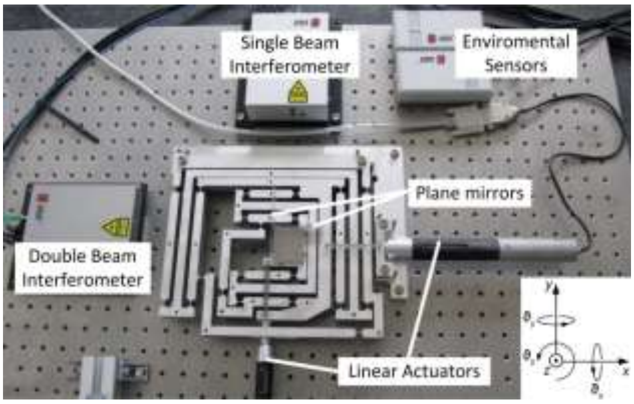

Figure 3. Test bench for measuring the motion path of the planar stage prototype

To measure the motion in both directions two plane mirror interferometers are chosen, see figure 3. Additionally to the path of motion of the output link the rotation angle is measured. Therefore, one of the interferometers is a double beam interferometer with a known distance between the beams. Thus, the angle can be calculated. For an accurate measurement it is important to know the environmental parameters during the measurement, so they are also measured.

For the experimental characterisation of the planar stage three different parameters of motion are measured and evaluated. The relative motion in *x* and *y* direction (Δx, Δy) is measured directly. The angle of the output q_z is calculated. In table 1 the results for the maximum positions of the planar stage are listed. The presented positions show the highest values for the deviations over the whole stroke of motion. Manufacturing tolerances ensure small deviations of the values obtained by simulation and measurement.

Table 1. Results of measurement for the motion of the output link of the planar stage prototyp

	Measurement			**Simulation**		
	$\lvert\Delta x\rvert$ [µm]	$\lvert\Delta y\rvert$ [µm]	q_z [´´]	$\lvert\Delta x\rvert$ [µm]	$\lvert\Delta y\rvert$ [µm]	q_z [´´]
$S_{in\ x}$ = 10 mm $S_{in\ y}$ = 0 mm	9985.5	2.8	6	9986.0	2.0	5.9
$S_{in\ x}$ = 0 mm $S_{in\ y}$ = 10 mm	1.2	9988.3	5	1.2	9999.4	5
$S_{in\ x}$ = -10 mm $S_{in\ y}$ = 0 mm	9987.7	2.3	3	9981.6	1.6	4.5
$S_{in\ x}$ = 0 mm $S_{in\ y}$ = -10 mm	1.1	9992.9	6	1.1	9999.8	6.2

Additionally the reproducibility of the parameters of motion is calculated. Hence, it is shown how accurate the planar stage can move in predefined positions. Investigations show reproducibility in the nanometre range.

5. Conclusion and outlook

The measurement results of the prototype show a very good correlation to the simulation results and the analytic calculations of the rigid-body model for the synthesis. It is shown, that the method of the angle-based synthesis is suitable to design a system, build from compliant mechanisms, for a given motion task.

This investigation proofs the benefits of contour variation of the flexure hinges in complaint mechanisms optimisation for the first time. Polynomial functions are a very good alternative compared to conventional contours because of their advantages regarding the strain in the hinges and the straight line deviation. The novel ten-hinge-mechanism is suitable for linear straight line motion.

In further investigations other compliant mechanisms will be integrated into the planar stage. This allows the positioning in more degrees of freedom, for example a rotation around the *x* and *y* axes. The goal is to combine all axes of motion in one point, the so called *Abbe point*. This allows the design and building of an open loop or closed loop positioning system with an ultra-high resolution, ultra-high reproducibility and minimised deviations.

Acknowledgments

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References

[1] Linß S 2015 Ein Beitrag zur geometrischen Gestaltung und Optimierung prismatischer Festkörpergelenke in nachgiebigen Koppelmechanismen. Doctoral thesis. Ilmenau: Universitätsverlag Ilmenau URN: urn:nbn:de:gbv:ilm1-2015000283