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Increasing the stroke of an ultra-precise compliant mechanism with optimised flexure hinge contours

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Abstract
This paper presents the investigations of the influences of the flexure hinges contours in compliant linkage mechanisms for precision engineering applications. Especially the influence on the precision of the path of motion and the stroke of the compliant mechanism is reflected. Based on previous investigations on optimised single flexure hinges [1] the validity of the proposed guidelines is analysed for an interconnection of flexure hinges in one mechanism. A parallel crank mechanism is used as an example for such a compliant rectilinear guiding mechanism. The parameters of the approximated linear motion are compared for the rigid-body model, compliant analytic model, FEM simulation models and measurements on manufactured prototypes.

Keywords: compliant mechanism, parallel crank mechanisms, linear motion, flexure hinge, contour, optimisation

1. Introduction

Compliant linkage mechanisms with flexure hinges are an interesting option for ultra-precise guides in precision engineering. They show advantages over conventional guides e.g. the path of motion is highly reproducible and they are free of debris, making them suitable for a vastly growing number of applications in clean room and vacuum environment. A disadvantage is that the path of motion is not an ideal straight line but shows a slight different character. Also the stroke is limited. Existing models that are used for the design of compliant mechanisms are based on simplified assumptions thus not properly representing the path of motion. New ways in the synthesis of compliant mechanisms are necessary. A vast improvement is given by the implementation of a more precise description of the flexure hinges by Linß [1]. This allows an optimisation of the contour of the flexure hinges as a part of the synthesis of the compliant mechanism. In this paper the parameters of the motion are compared for the rigid-body model, another analytic model based on the non-linear beam theory, FEM simulation models and measurements on manufactured prototypes.

In this article investigations are carried out using the example of a parallel crank, with different contours of the flexure hinges.

2. Modelling of the compliant mechanism

The rigid-body model of the parallel crank is the starting point for the synthesis of the compliant linkage mechanism. Following a dimensioning of the geometric parameters, like the lengths of the coupler and the cranks, the path of motion of the coupler is calculated for the rigid-body model. In the following investigations these parameters are taken as constant. In a next step an analytical investigation of the path of motion of the coupler is done by a model based on the non-linear beam theory established by Nönnig [2]. To investigate the influence of the contour of the flexure hinges, a CAD model of the parallel crank mechanism with implemented flexure hinges is used as the basis for FEM simulations. The geometric parameters for the flexure hinges are shown in figure 1a. Some of these parameters are constant for all the simulations and measurements: $h/H = 0.03$; $H = l = 10$ mm; $B = 6$ mm [3]. Three different contours are used: semi-circular, corner-filleted and polynomial with 6th order (figure 1b-d).

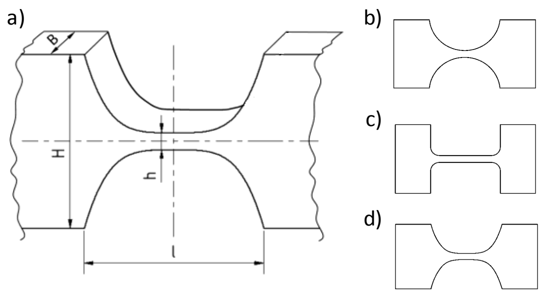

Figure 1. The shape of the investigated flexure hinges:
a) geometric parameters and
b) flexure hinge contours: (I) semi-circular, (II) corner-filleted, (III) polynomial

3. Measurement setup

To verify the theoretical models measurements are done based on manufactured prototypes. Therefor the displacement in y-direction v_y and the angle of the coupler φ is measured and analysed. Interferometric length measurement systems are used to allow nanometre resolution. The displacements in x-direction v_x and in y-direction v_y are measured by single-beam-interferometers. To determine the angle φ a third beam is added. Thus the difference in the length measurement and the known base width of two beams allows the calculation of the angle of the coupler (figure 2). For each prototype more than ten series of measurement are done, to gain a sufficient level of confidence.

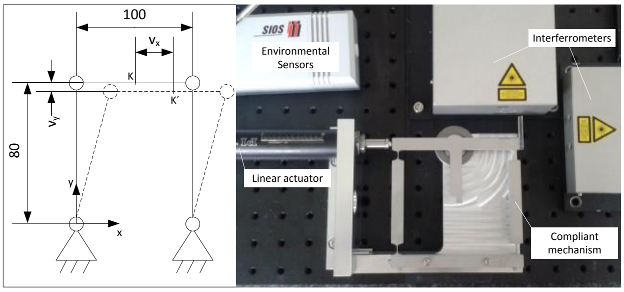

Figure 2. Test bench for the measurement of the displacements v_x, v_y and the angle φ of the compliant parallel crank mechanism

The motion of the mechanism is induced by a linear actuator with a resolution of 0.1 µm. The transmission of force is placed directly at one side of the coupler (figure 2). To eliminate influences by the dead weight of the mechanism a counter balance in form of a rolling sphere is added.

4. Comparison of the results

The results for the parameters of motion are presented for five models and measurements of three prototypes. All graphs of figure 3 show the same characteristics, but slight differences in the absolute values.

To verify the models in dependence of the flexure hinge contours a comparison with the rigid-body model is done. The path of motion of the rigid-body model is an idealised geometrical path. The results are shown in figure 4.

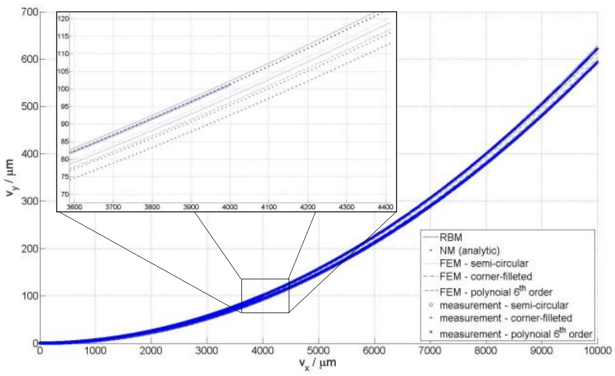

Figure 3. Motion path of the coupler point of the parallel crank mechanism for the rigid-body model (RBM) and the compliant mechanism (CM) analytical, FEM simulations and measurements

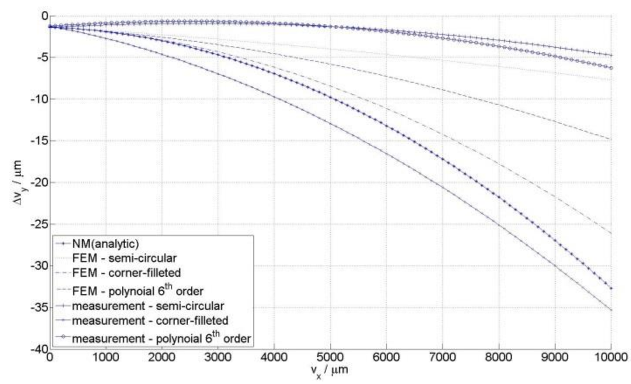

Figure 4. Relative differences Δv_y of the models and prototypes in comparison to the rigid-body model for the compliant mechanism (CM) analytical, FEM simulations and measurements

The deviation between simulated and measured models with the same flexure hinge contour can be seen too. The deviations are prone to several impacts, like manufacturing and material of the prototypes as well as the quality of the theoretical models. Results of two of the contours are close to the rigid-body model both in simulation and in the measurements. These are the semi-circular and the polynomial contour with 6th order. Compared to semi-circular the polynomial contour allows longer usable stroke of the mechanism. The stroke of the motion is limited by the yield strength. The values for the maximum strokes are determined by the FEM simulation. For the semi-circular contour it is v_x = 4 mm and for polynomial with 6th - order it is v_x = 10 mm.

The angle of the coupler φ is zero since there is no torque stress in the rigid-body model. In the other models it is different from zero, but for the considered stroke negligibly small in the range of some arc seconds. With the analytical model established by Nönnig and the FEM models it is possible to determine an exact value. The angular resolution of the presented measuring setup is limited to 4”. Measured values are in this level. Therefore it can only be assured that the angle φ is below the value of 10”.

5. Summary and outlook

In the presented investigations on the stroke of planar compliant guiding mechanisms the focus is on the contour of the flexure hinges. On the example of a parallel crank mechanism it is shown, that the contour of the flexure hinges has a non-negligible influence on the precision of the path and the usable stroke of motion. By means of conventional contours (semi-circular, corner-filleted) optimisation can only be done whether for the precision or the stroke of the path of motion. With the help of polynomial contours it is possible to optimise both parameters of motion by the order of the polynomial function. The motion of these mechanisms is simulated. To verify the simulation carefully manufactured prototypes are measured.

In further investigations more influential parameters of the contour of the flexure hinges will be investigated. The accuracy of the manufacturing of the prototypes or different parameters of the force on the mechanism, like direction, application point or value, will be of interest. In terms of the measurement setup there will be an increase of the precision by improved angular measurement allowing detecting differences in the path of motion of mechanisms with various contours of flexure hinges.

The main goal of the investigations is to establish guidelines for higher quality synthesis of the design of compliant linkage mechanism usable for ultra-precise applications.

Acknowledgments

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