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MODEL-BASED DESIGN OF FLEXURE HINGES FOR RECTILINEAR GUIDING WITH COMPLIANT MECHANISMS IN PRECISION SYSTEMS

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Abstract

Flexure hinges are often used in precision systems because in addition to other advantages they allow the simple adjustment of a required deformation and motion behavior of monolithic compliant mechanisms by geometrical design. In this contribution, the potential of improving the motion precision as well as the motion range by specific design of the flexure hinge dimensions and in particular of their notch contour is described using the example of two four-bar compliant rectilinear guiding mechanisms. To verify the detailed investigation of the notch contour as a recent approach of the compliant mechanism synthesis, the model-based FEM results are compared to the guiding error of the rigid body counterparts.

Kurzfassung

Festkörpergelenke werden vielfach in Präzisionssystemen eingesetzt, weil sie die einfache Einstellung eines gewünschten Verformungs- und Bewegungsverhaltens von monolithischen nachgiebigen Mechanismen durch geometrische Gestaltung ermöglichen. Im Hinblick auf einen vergrößerten Bewegungsbereich und eine erhöhte Bewegungspräzision wird in diesem Beitrag das Potenzial der Gestaltung der Abmessungen und insbesondere der Aussparungskontur der Festkörpergelenke beispielhaft an zwei nachgiebigen Geradführungsmechanismen beschrieben. Um den neuen Syntheseansatz der modellbasiert ermittelten FEM-Ergebnisse zu verifizieren, werden die Führungsfehler mit denen der Starrkörpermechanismen verglichen.

1. Introduction

For guiding and transfer tasks, where a high precise motion is needed, often compliant mechanisms are used. Their mobility is made possible by the elastic deformation of material coherent joints ([1], [2], [3]). Because of their advantages, compliant mechanisms have been established as monolithic linkage mechanisms in many technical fields of application. In these solid-state mechanisms, the flexibility is achieved only by flexure hinges which fulfill the function of conventional revolute joints but limited to small angular deflections of a few degrees. The research aims to influence the motion and deformation behavior of compliant parts in precision systems by geometric design, choice of material or a combination of both (e.g. [4], [5] [6]).

Due to modern manufacturing technologies and new materials compliant mechanisms with concentrated distribution of compliance are state of the art in precision systems, like many applications in microsystems technology, precision engineering or metrology show. Therefor usually prismatic flexure hinges with cut-outs are used. Because in most cases basic notch contours such as circular or corner-filleted contours are used, these flexure hinges have a limited motion range and accuracy. The demand of a larger angular deflection and a low shift of the rotational axis therefore result in very complex flexures (e.g. [7], [8]) or in an increased number of joints in the entire system (e.g. [9], [10]). With few exceptions, the notch contour optimization of flexure hinges with regard to both of the mentioned criteria is not subject of research [11].

Many influences related to the geometric design of flexure hinges are not yet adequately investigated. This includes in particular the effect of the shift of rotational axis of single flexure hinges on the motion behavior of the entire compliant mechanism. For four-bar and multi-chain compliant mechanisms in the literature, the advantages of using long beam joints compared to film or notch joints in terms of the achievable range of motion are described [12]. Furthermore, there exist studies of different compliant guiding mechanisms based on flexure hinges with varied hinge dimensions ([13], [14]) as well as comparative investigations how notch hinges with different standard contours influence the motion behavior [2]. However, for precision engineering applications, the rectilinear guiding accuracy is particularly defined by the notch contour of the flexure hinges too [6]. Therefore, the notch contour must be considered regarding the synthesis of the compliant mechanism.

2. Material and method

Because the resulting stroke – which is limited i.a. by allowable stress –, the stiffness and especially the precision of motion of compliant mechanisms are defined by several different geometric parameters, the aim of this work is to investigate the design of the flexure hinge contour and dimensions as well as the compliant mechanism itself. Regarding the three mentioned characteristics, the model-based investigation is exemplified for two types of compliant rectilinear guiding mechanisms: the four-bar linkage after ROBERTS and EVANS with a symmetric respective asymmetric coupler point curve.

In contrast to the synthesis of rigid body mechanisms for the compliant mechanisms synthesis the stress and deformation behavior as well as the motion behavior must be considered as multi-objective design criteria. Starting from the rigid body mechanism, this leads to a complex and iterative model-based design process for compliant mechanisms with concentrated compliance. The investigations in this contribution are based on the following approach:

- synthesis of structure and dimensions of the rigid body mechanism,
- modeling of the compliant mechanism,
- modeling of the flexure hinges,
- parameter identification,
- investigation of the compliant mechanism related to the variation of the geometric parameters with the help of finite elements method,
- verification of results and if necessary iterative improvement.

This enhanced synthesis method differs from previous approaches (e.g. [14], [15]) in considering especially the influence of the notch contour as a function of the hinge dimensions on the motion precision of compliant rectilinear guiding mechanisms. Therefore, optimized notch contours, which are determined as a result of recent studies [16], are investigated in addition to standard hinge geometries like circular or elliptical contours.

The aim of the geometrical design of the compliant rectilinear guiding mechanisms and their flexure hinges presented here is to investigate the translational guiding accuracy (respective the normal guiding error) of a coupler point for a given maximum input deflection of 10 mm in horizontal direction. Furthermore, the occurring maximum stresses and the stiffness are evaluated. Subject of the model-based investigations are compliant mechanisms with the following characteristics: a planar motion, a prismatic body with rectangular cross section and a symmetric notch contour of the flexure hinges. The material which is used for the FEM analysis is the aluminum alloy EN AW 7075 with linear elastic material behavior and the following properties: $E = 72$ GPa, $\mu = 0.33$ und $\rho = 2.8$ gcm^{-3}. To verify the FEM results, the guiding accuracy of the compliant mechanism is compared to the error of the rigid body mechanism.

2.1. Modeling and investigation of the rigid body mechanism

The EVANS and ROBERTS four-bar linkages realize the guiding of a coupler point on an approximate rectilinear path. Respecting suitable geometry conditions for the dimensions as well as the joint coordinates, these rectilinear guiding mechanisms allow a guiding accuracy of a coupler point in the micrometer range according to the kinematic structure of the crank-and-rocker mechanism and the symmetric double-crank mechanism. The regarded coupler point *C* is located at the end of the coupler (EVANS mechanism) and in the corner of the coupler as a ternary link (ROBERTS mechanism), as shown in Fig. 1. The optimal values of link lengths for which the mechanisms realize the best guiding accuracy are determined after [17].

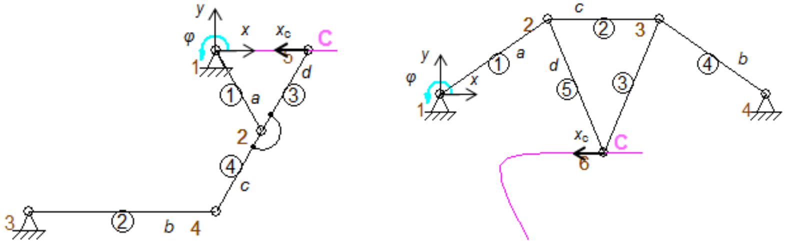

Fig. 1: Rigid body model and motion analysis of the two investigated mechanism types with sections of the coupler point curves: four-bar linkage after EVANS (l.) and after ROBERTS (r.)

To find the initial position of the mechanism, i.e. to determine the position of the input crank that leads to a minimal vertical error y_C during the horizontal guiding between realized and exact rectilinear path, the motion behavior of both mechanisms is investigated with the software SAM. The chosen link lengths, the initial positions and the resulting errors are shown in Table 1.

Tab. 1: Geometrical parameters of the investigated rigid body mechanisms and resulting guiding accuracy for a given displacement

four-bar linkage after	a [mm]	b [mm]	c [mm]	d [mm]	φ [°]	input x_c [mm]	output y_c [µm]
EVANS	50.0	100.0	50.0	50.0	300	-10	-55.7
ROBERTS	66.6	66.6	56.6	73.6	35	-10	-25.2

2.2. Modeling the compliant mechanism

Based on the determined rigid body mechanism the compliant mechanism is built up as a monolithic solid body in the CAD model. Thus, the center points of the flexure hinges are equal to the coordinates of the four revolute joints of the rigid body mechanism.

But since the geometrical design of the links of a compliant mechanism has an influence on the motion behavior too, two opposite coupler shapes are investigated for both compliant mechanism types, cf. Fig. 2.

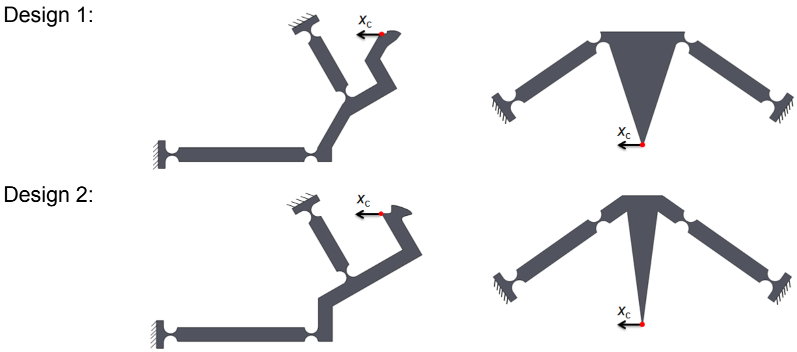

Fig. 2: Solid state model of the two investigated compliant guiding mechanisms with two different shape versions for the coupler (exemplarily shown with circular flexure hinges): four-bar linkage after EVANS (l.) and after ROBERTS (r.)

2.3. Modeling the flexure hinges

For the flexure hinges, prismatic and symmetric notch contours are used. Geometrical parameters of the hinge dimensions are the hinge length *l*, the hinge height *H*, the hinge width *B* and the minimal notch height *h*.

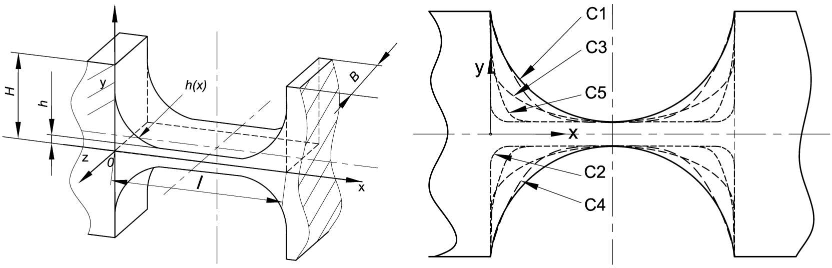

Fig. 3: Basic hinge dimensions (l.) and the five investigated notch contours of the flexure hinges (r.) with C1 – circular ($2R = H$), C2 – corner filleted with stress-optimal radius ($r = 0.1l$) after [6], C3 – elliptical ($r_a = 2r_b = H$), C4 – bi-quadratic polynomial and C5 – 16th-order polynomial contour after [16]

For the design of experiments, the variable hinge height $h(x)$ of all four flexure hinges of the compliant mechanisms (cf. Fig. 2) is described with one of the five notch contours, shown in Fig. 3.

2.4. Design parameters and FEM analysis

For the structural three-dimensional FEM analysis ANSYS WORKBENCH is used and large deflection (nonlinear geometry) is considered. As boundary condition fixed supports are applied at both stationary revolute joints. As input a horizontal displacement $x_c = 10$ mm is introduced at the coupler point C divided into three load steps while the vertical displacement is set to be free. The output results from the FEM simulations are guiding accuracy, maximum equivalent stress and stiffness due to the force which is required for the applied displacement.

The hinge height and the hinge width are chosen to be constant as $H = 10$ mm and $B = 6$ mm for all investigations. Three important geometrical attributes of the compliant mechanism respective the flexure hinges are investigated, resulting in a total number of 90 different compliant mechanisms for each of the both mechanism types:

- the coupler shape (two designs, see Fig. 2),
- the notch contour of the flexure hinge (five contours see Fig. 3) and
- the hinge dimensions l and h (nine different combinations with $l = 5$, 10, 20 mm and $h = 0.3$, 0.5, 1 mm).

3. Results

The FEM results for the guiding accuracy y_c, maximum equivalent stress σ and stiffness c are shown for the four-bar linkage after EVANS (cf. Fig. 4) and ROBERTS (cf. Fig. 5) as a function of the three geometrical attributes l, h and the notch contour for both design versions of the coupler shape.

4. Discussion

To realize a precise rectilinear guiding no specific notch contour is optimal in general because the motion behavior of compliant mechanisms depends on several geometrical parameters to the same degree. The following and to some extend novel results can be concluded regarding the guiding error:

- the coupler shape, the hinge dimensions and in particular the notch contour of the flexure hinges have a strong influence on the guiding accuracy,
- comparing all determined guiding errors with the values for both rigid body mechanisms (cf. Table 1) it is possible to realize a lower but in many cases even a higher accuracy with compliant mechanisms,
- longer hinges cause higher errors while the effect of varying the minimal notch height depends on the mechanism type,
- the influence of the notch contour increases with an increasing hinge length,
- circular contours are suitable for thin hinges as they realize the best accuracy while corner-filleted contours lead to the highest errors, but as the results for the ROBERTS mechanism show, this correlation not exists for thick hinges in general.

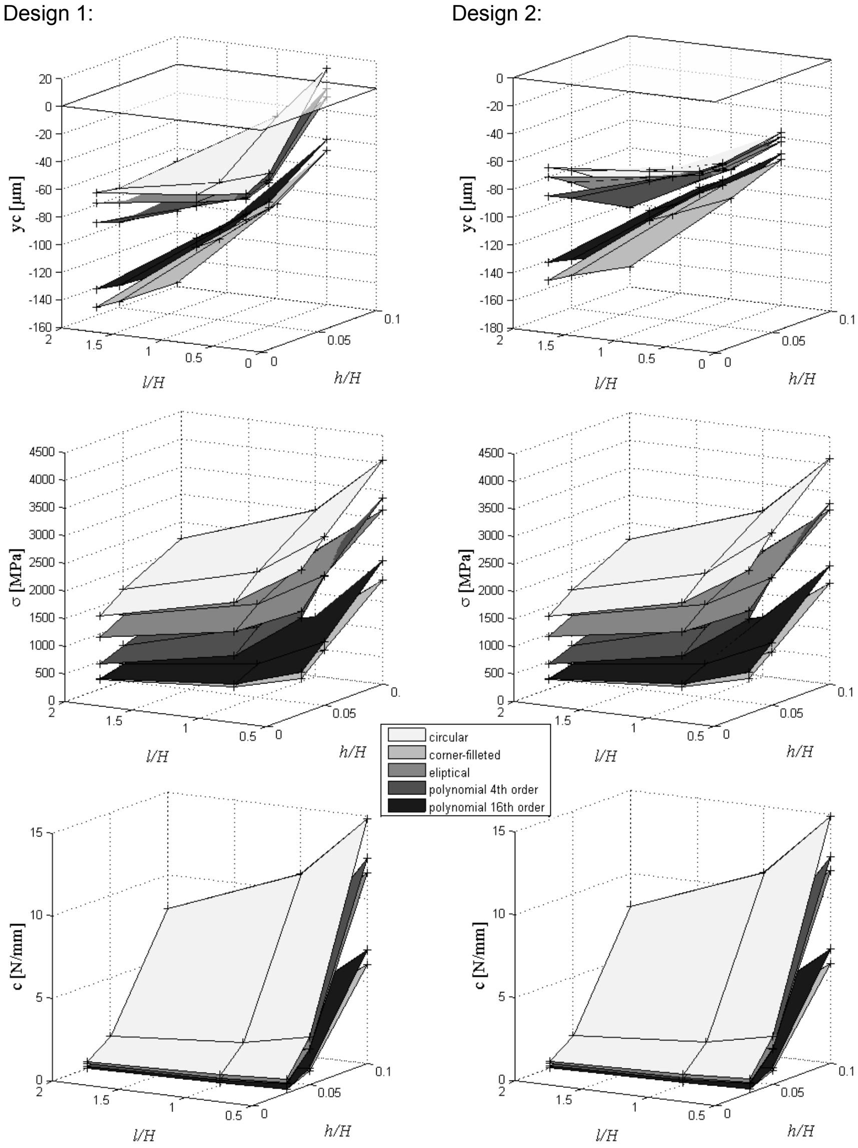

Fig. 4: FEM results for the two design versions of the four-bar linkage after EVANS due to an input displacement x_c = 10 mm: guiding accuracy (top), maximum stress (center) and stiffness (bottom)

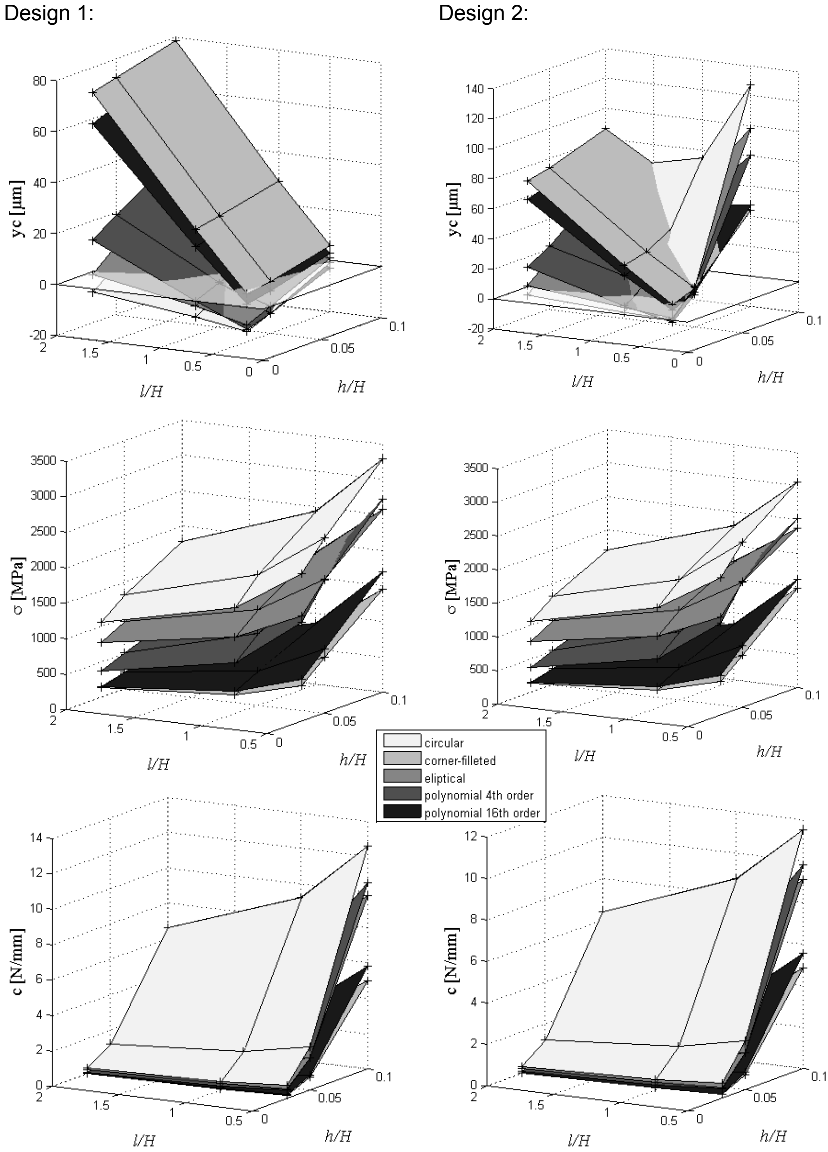

Fig. 5: FEM results for the two design versions of the four-bar linkage after ROBERTS due to an input displacement x_c = 10 mm: guiding accuracy (top), maximum stress (center) and stiffness (bottom)

Regarding the maximum equivalent stress, which limits the possible stroke, the results for both mechanism types show, that the design of the coupler shape has an insignificant influence on the stress behavior. But depending on the geometrical parameters of the flexure hinge, the following qualitative correlations can be observed:

- the stress values decrease with a larger ratio l/h and they increase with a larger ratio of h/H,
- the influence of the contour variation can be as large as the effect of changing the minimal notch height h and even larger as the effect of changing the hinge length l,
- circular contours cause very high stresses while corner-filleted and 16th-order polynomial contours allow low stress values and thus this stress-optimized contours are suitable regarding the motion range.

The deformation behavior of both mechanism types is also independent from the coupler shape design. But variations of the flexure hinge parameters influence the stiffness of the mechanism as follows:

- shorter and thicker hinges lead to increased stiffness values, while the influence of length variation is negligible for very thin hinges,
- the influence of the contour variation can be as large as the effect of changing both hinge dimensions,
- corner-filleted and 16th-order polynomial contours lead to low stiffness values while circular contours cause a high stiffness.

5. Conclusion

In this contribution, the potential of improving the guiding accuracy and the motion range of compliant mechanisms by geometrical design of the flexure hinge dimensions and in particular of their notch contour is described.

Regarding the detailed investigation of the notch contour as a newly considered part of the compliant mechanism synthesis the results confirm that it is possible to suggest suitable contours for the whole mechanism by analyzing the stress and deformation behavior of only one single flexure hinge. Because of the multi-criterial dependencies this approach is not possible for the motion behavior in general. Pivot optimal notch contours like circular flexure hinges realize nearly in most cases a very precise guiding. But as the investigations show, stress-optimal corner filleted contours allow on the one hand a large stroke and low stiffness in general and – depending on the hinge dimensions – a high guiding accuracy in some cases too.

To satisfy a large stroke and a high accuracy at once also optimized notch contours based on predefined and freeform geometries, e.g. the investigated polynomial contours, can have high potential. But since the linkage or coupler shape has influence on the motion behavior of the mechanism too, further investigations of these dependencies as well as the systematical research of the center shift of the flexure hinge itself are remaining challenges regarding the compliant mechanism synthesis.

References

[1] Howell, L. L.; Midha, A.: A Method for the Design of Compliant Mechanisms with Small-Length Flexural Pivots. In Journal of mechanical design, 1994, 116; S. 280–290.

[2] Christen, G.; Pfefferkorn, H.: Nachgiebige Mechanismen. Aufbau, Gestaltung, Dimensionierung und experimentelle Untersuchung: VDI-Berichte Nr. 1423 1998; S. 309–329.

[3] Lobontiu, N.: Compliant mechanisms design of flexure hinges. CRC Press, Boca Raton, Fla., 2003.

[4] Modler, K.-H.; Modler, N.: Aktive textilverstärkte Nachgiebigkeitsmechanismen (A-TNM): 8. Kolloquium Getriebetechnik 2009, 2009; S. 197–208.

[5] Zentner, L.; Böhm, V.; Minchenya, V.: On the new reversal effect in monolithic compliant bending mechanisms with fluid driven actuators. In Mechanism and Machine Theory, 2009, 44; S. 1009–1019.

[6] Linß, S.; Zentner, L.: Gestaltung von Festkörpergelenken für den gezielten Einsatz in ebenen nachgiebigen Mechanismen: 9. Kolloquium Getriebetechnik 2011, 2011; S. 291–311.

[7] Henein, S. et al.: Flexure pivot for aerospace mechanisms: Proceedings of the 10th European Space Mechanisms and Tribology Symposium, 2003.

[8] Martin, J.; Robert, M.: Novel Flexible Pivot with Large Angular Range and Small Center Shift to be Integrated into a Bio-Inspired Robotic Hand. In Journal of intelligent material systems and structures, 2011, 22; S. 1431–1438.

[9] Ivanov, I.; Corves, B.: Flexure hinge-based parallel manipulators enabling high-precision micro manipulations: Proceedings of the 1st Workshop on Microactuators and Micromechanisms MAMM, 2010.

[10] Cosandier, F.; Chatagny, V.; Clavel, R.: Optimizing the Design of the 13-Hinge Rectilinear Stage for High Straightness Translation: Proceedings of the 13th World Congress in Mechanism and Machine Science, 2011; S. 8.

[11] Linß, S. et al.: The influence of asymmetric flexure hinges on the axis of rotation: Proceedings of the 56th International Scientific Colloquium, 2011.

[12] Pavlovic, N. T.; Pavlovic, N. D.: Mobility of the compliant joints and compliant mechanisms. In Theoretical Applied Mechanics, 2005, 32; S. 341–357.

[13] Pavlovic, N. T.; Pavlovic, N. D.: A design of evans compliant four-bar linkage for rectilinear guiding: Proceedings of the 3rd International Conference ″Research and Development in Mechanical Industry″ RaDMI 2003, 2003; S. 425–432.

[14] Pavlovic, N. T.; Pavlovic, N. D.: Compliant mechanism design for realizing of axial link translation. In Mechanism and Machine Theory, 2009, 2009; S. 1082.

[15] Modler, N. et al.: Auslegung und Gestaltung von Nachgiebigkeitsmechanismen: Bewegungstechnik 2010. Koppelgetriebe, Kurvengetriebe und geregelte Antriebe. VDI, Düsseldorf, 2010; S. 177–190.

[16] Linß, S.; Erbe, T.; Zentner, L.: On polynomial flexure hinges for increased deflection and an approach for simplified manufacturing: Proceedings of the 13th World Congress in Mechanism and Machine Science, 2011.

[17] Wazan, O.: Rechnergestützte Untersuchung und Auswahl von Koppelmechanismen für Geradführungen. Dissertation, TU Ilmenau, 2005.