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Research paper

Influence of geometric scaling on the elasto-kinematic properties of flexure hinges and compliant mechanisms

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ABSTRACT

Flexure hinges with notches are typical elements in high-precision compliant mechanisms with a wide variety of sizes from macro to micro or nano applications. This paper investigates the elasto-kinematic hinge and mechanism properties in dependence of scaling the geometric parameters regarding the impact of using optimized flexure hinge contours within a unified synthesis method without the need of rerunning simulations. The three performance criteria stiffness, maximum strain, and precision are analyzed among others for a single symmetric flexure hinge and a parallel four-bar linkage. The analytical investigations and FEM simulations include semi-circular, corner-filleted, and special 6^{th}-order polynomial hinge contours. Accordingly, the chosen rigid-body model is transferred into a compliant mechanism through replacing all revolute joints by notch hinges. Geometric scaling is investigated with a parametric non-linear FEM model for factors from 0.1 to 2. To obtain results for comparable relative hinge angles, the defined input displacement is scaled too. Three prototypes are tested to verify the simulations and to validate the influence of scaling by measurement. In addition to general scale dependencies of the properties it is shown, that optimized flexure hinge contours are promising for miniaturized compliant mechanisms with high precision and large stroke at once.

1. Introduction

For technical applications in precision engineering compliant mechanisms with flexure hinges [1–3] are often used instead of rigid-body mechanisms. Due to their monolithic design compliant mechanisms are suitable to realize high reproducible motion without clearance, friction and wear. Thus, compliant mechanisms with lumped compliance are established in challenging environments, like vacuum, space and cryo applications (e.g. [4–6]). Furthermore, they are used in high-precise optical micro or nano positioning systems (e.g. [7–9]) and they are typical in grippers, manipulators and sensors with macro (e.g. [10–12]), micro (e.g. [13–15]) or nano [16] size scale.

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In such compliant mechanisms mostly notch flexure hinges [17] are used as material coherent revolute joints to realize an approximated rotation of two adjacent link segments due to the elastic deformation in the hinge. In dependence of the geometry and material, rotation angles over 70° can generally be realized, for example, with plastic film joints [18]. But for high-strength metals which are typical for notch hinges in monolithic micro and nanopositioning systems, the rotation is limited to small angles of a few degrees [19]. The demand for a larger angular deflection and a low shift of the rotational axis results in a variety of further and sometimes very complex flexure hinge types, like the pre-curved leaf-type hinge [20], the cartwheel hinge [21], the serial cascaded cartwheel hinge [22] or the butterfly hinge [5]. Another approach is using superelastic notch hinges, which can reach angles of up to 30° for optimized notch shapes [23]. However, the investigations in this paper are focused on notch flexure hinges for which basic cut-out geometries, like circular or corner-filleted contours, are mostly used. Due to their low complexity notch hinges are easy to manufacture and therefore mainly used in plane compliant mechanisms, especially for kinematic chains with a higher link number. Furthermore, the notch contour of flexure hinges enables optimization potential regarding the rotational precision and possible deflection as equivalent objectives, which is not used yet.

In contrast to the synthesis of a rigid-body mechanism the stress and deformation behavior as well as the motion behavior must be considered as multi-objective design criteria in the compliant mechanism synthesis. Starting from the rigid-body model, this leads to a complex and iterative model-based design process for compliant mechanisms. Hence, for compliant mechanisms only a few design guidelines and usually numerical methods exist and simulations are needed. In addition, the step of the geometric design of the flexure hinges is a key aspect in the synthesis of a compliant mechanism with regard to the required mechanism properties. In literature, the specific geometric design of the incorporated flexure hinges during the synthesis is only considered for the use of standard contours [24] with almost identical hinges in one compliant mechanism. Existing calculations are often made with respect to concrete applications. Therefore, the approaches of regarding complex flexure hinge types within the mechanism (e.g. [25,26]) or increasing the hinge number in the kinematic chain of the mechanism (e.g. [27,28]) are used. In addition, especially the angle-based contour optimization of polynomial notch hinges and the use of different hinge contours in one mechanism offer potential for high-precise and large-displacement compliant mechanisms [29–31].

Due to the increasing use of flexure hinges and compliant mechanisms in miniaturized and micromechanical systems, the influence of scale has to be considered within the design process, too. A unified approach which considers the notch contour optimization with regard to the kinematic properties especially has not been made so far. But starting from a mechanism with a known behavior (e.g. from literature or own results) the trace of a dedicated point on a follower or of a whole plane (e.g. stroke of straight-line motion) can be adopted to the requirements by scaling the mechanism with constant link length ratios slightly and additional optimization (e.g. [10]). This approach is also state of the art for designing MEMS-based compliant mechanisms, were a well-known mechanism is often selected, transferred and miniaturized (e.g. [14]). If the change ratios of the elasto-kinematic properties due to scaling were known, the design of the compliant mechanism is then easily possible without rerunning many time-consuming simulations. Thus, there is a research need to systematically investigate the impact of optimized notch contours for scaled compliant mechanisms with the focus on miniaturization.

This paper addresses the investigation of the most important deformation and motion properties of flexure hinges and compliant mechanisms in dependence of the geometric scaling factor and the hinge contour. Among the variety of existing notch geometries, three flexure hinge contours are selected: The usual semi-circular and corner-filleted contours and a special polynomial contour of 6th order. After describing the rigid-body replacement method briefly, two approaches, the uniform scaling and non-uniform scaling, are introduced in Section 2. The scale-dependent elasto-kinematic flexure hinge properties are investigated in Section 3 by means of non-linear analytical calculations and large-deflection Finite Element Method (FEM) simulations. In Section 4, the example of a parallel four-bar linkage is used for simulative investigations of the mechanism properties in dependence of the scaling factor and the three hinge contours. In addition to this, further parameters, like the minimum notch height and the load acting position, are investigated with the parametric non-linear FEM model for scaling factors from 0.1 to 2. To obtain results for comparable hinge angles, the defined input displacement is scaled, too. Three prototypes are tested to verify the simulations and to validate the influence of scaling by measurement. The main results are summarized in Section 5 with regard to the synthesis of compliant mechanisms. Finally, conclusions are drawn in Section 6.

2. Flexure hinges and compliant mechanisms

First, the method of replacing all hinges in the rigid-body model with flexure hinges in the compliant mechanism is described, see Fig. 1. Second, the geometric scaling of compliant mechanisms is introduced for two approaches using a parallel four-bar linkage as an example.

2.1. Rigid-body replacement method and design of notch flexure hinges

For synthesizing a compliant mechanism three general approaches exist: the synthesis through rigid-body-replacement method (e.g. [32]), the synthesis through topology optimization method (e.g. [33]) and the synthesis through constrained-based methods, like the freedom and constraint topologies method (e.g. [34]) or the building blocks method (e.g. [35]). In dependence of the chosen approach, compliant mechanisms with a different structural design and distribution of compliance

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