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Elasto-kinematic comparison of flexure hinges undergoing large displacement

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ABSTRACT

The design of precision compliant mechanisms requires the assessment of the elasto-kinematic characteristics of the flexure hinges connecting bulky parts. Due to geometrical nonlinearities, a comprehensive analysis requires the functional properties to be evaluated within the feasible range of relative displacement. This investigation proposes the use of kinematic invariants to characterize the main features of a compliant mechanism. In particular, this paper offers the comparison of five common flexure hinges in terms of the relative motion kinematic invariants. By using the dynamic spline formulation, for each hinge typology, a flexible multibody model is developed to obtain the fixed and moving centrodes and the diameter of the inflection circle of the relative motion. In order to fully characterize the elasto-kinematic behaviour, the simulative models are also used to compute the equivalent stiffness as a function of the rotation angle. The results show that the differences among the various types of hinges is relevant in terms of both kinematic and compliance characteristics. The findings and the methodology herein outlined are new tools for the optimal design and synthesis of flexure joints.

1. Introduction

The mobility of a compliant mechanism is due to the deformation of its parts rather than to the inclusion of kinematic pairs, as in traditional mechanism [1]. A compliant mechanism is often manufactured as a single piece of material and it does not possess any discrete degree of freedom in a strict sense. These mechanisms are widely used in different fields of application, from robotics, to micromechanics, to aerospace and biomechanics. In order to simplify the design of such devices, engineers often localize deformation zones, as to mimic the presence of standard kinematic pairs (i.e. virtual hinges). Mechanisms with lumped compliance emulate the traditional rigid-link ones, where kinematic joints are replaced with flexure hinges. Consequently, methods conceived to design traditional mechanisms can be adapted accordingly. In fact, the well-known pseudo-rigid body approach is based on the outlined criterion [2,3].

Generally speaking, flexure hinges are able to undergo large deformation and connect stiff links (almost undeformable). When compared to classical joints, they have several advantages, including the absence of assembly procedure, negligible friction loss, clearance and wear (there are no sliding parts). Moreover, they have an intrinsic elasto-kinematic behaviour that has both positive and negative consequences. As with a standard spring elements, flexure hinges generate a reaction against the deformation. This property can be useful because, in the same compliant joint, there are the capabilities of movement and reaction using a single structure. On the other side, the kinematic behaviour is affected by the loads acting on the hinge. In precision mechanics and control systems this is often undesirable. These considerations motivated many scientific contributions on the flexure hinge performances,

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especially when the displacements become large [4,5], and specific design methodologies are available [6–9]. In most of the cases, numerical approaches based on finite elements are used [10,11], but scientific literature also reports analytical studies for simple cases [12,13].

The above mentioned studies are mainly focused on structural and elastic performance of the flexure hinges. On the other hand, in precise applications, it is also important to assess the elasto-kinematic behaviour in the whole range of deformation. Most of the contributions in literature investigate the relative motion of two bodies connected by a flexure hinge in terms of rotation pole (finite or instantaneous) [14].

In particular, on this topic, Venanzi et al. [15] pointed out the importance of the position analysis of compliant mechanism with different types of flexure hinges. Few years later, Linb et al. [16] assessed the influence of asymmetric flexure hinge on the location of the axis of relative motion. More recently, Guo et al. [17] proposed an equivalent pin model in order to address the simulation of leaf hinge taking into account the moving rotation centre. Verotti et al. investigated the possibility of designing a flexure hinge based on the theory of conjugate surfaces [18]. On year later, he also suggested an analytical expression to locate the centre of rotation in a curved flexure hinge [19].

The main original contribution of the present paper is the comparison, based on instantaneous kinematic invariants [20–23], of the elasto-kinematic behaviour for five types of common flexure hinges connecting two bulky rigid bodies. According to the authors' best knowledge, the analysis of kinematics invariants in flexure hinge design and a direct comparison among different solutions have never been addressed in previous studies. This investigation is motivated by the observation that the invariants, such as the fixed and moving centrodes and the inflection circle, characterize the relative motion, independently from the actual structural embodiment [21]. Therefore, the relative motion between the rigid bodies coupled with the hinge, under predefined boundary conditions, is analysed in terms of instantaneous kinematics invariants. The equivalent overall elastic characteristics (the spring-like reaction of the hinges), within the whole range of deformation, is also assessed. Due to the necessity of including geometrical nonlinearities of large displacements, the investigation makes use of numerical models developed with the dynamic spline flexible multibody formulation [24]. This results into a compact and efficient simulations of slender flexible structures undergoing large displacements, as in other compliant mechanisms analyses [25,26].

The paper is organized as follows. In the first part, the flexure hinge types under investigation are introduced. In the second part, the details of the numerical simulative models are presented. In the third part, the results of both kinematics and compliance investigations are presented and discussed.

2. Flexure hinge description and modelling strategy

The five compliant hinges considered in the study, depicted in Fig. 1, are the circular profile flexure hinge, the elliptical profile flexure hinge, the leaf flexure hinge, the solid flexure cross hinge and the two-flexure cross hinge. These joints are widely used in compliant mechanisms.

The circular and elliptical profile flexure hinges are characterized by a localized necking in the middle. They differ due to the

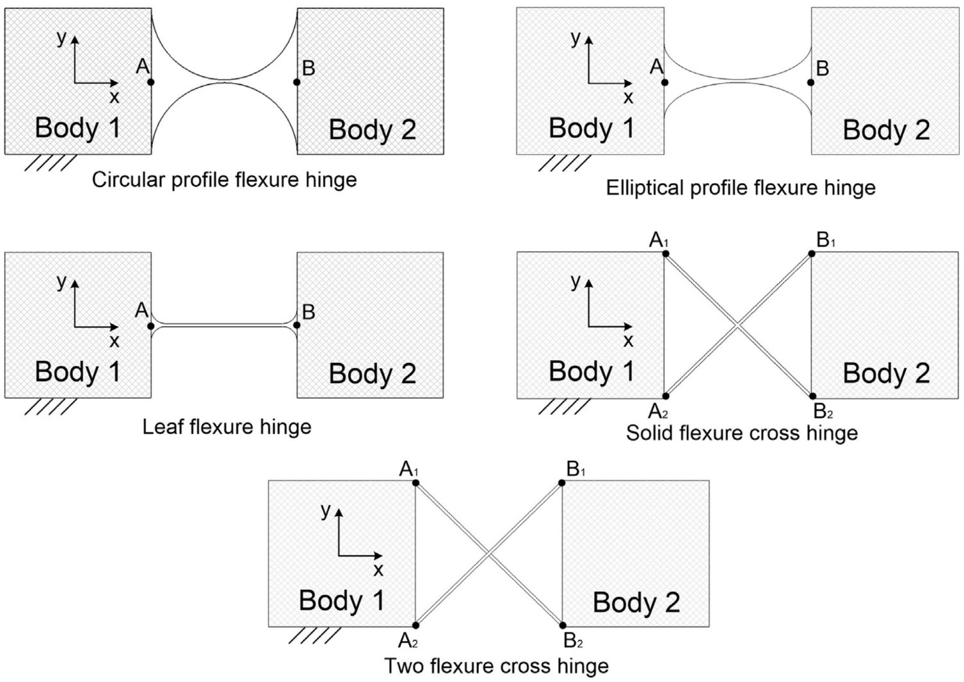

Fig. 1. The five flexure hinges under investigation.