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Analytical compliance analysis and finite element verification of spherical flexure hinges for spatial compliant mechanisms

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ABSTRACT

This paper introduces and investigates a novel Spherical Flexure (SF), specifically conceived for application on spherical compliant mechanisms. The flexure features an arc of a circle as a centroidal axis and an annulus sector as cross-section, circle and annulus having a common center coinciding to that of the desired spherical motion. In this context, each element of the SF spatial compliance matrix is analytically computed as a function of both flexure dimensions and employed material. The theoretical model is then validated by relating analytical data with the results obtained through three-dimensional Finite Element Analysis. Finally, SFs are compared to Circularly Curved-Beam Flexures (CCBFs) in terms of parasitic motions.

1. Introduction

Flexure hinges can profitably substitute traditional kinematic pairs in those articulated mechanisms which require absence of backlash and friction but restricted range of motion. Common applications span high precision manufacturing [1,2], minimally invasive surgery [3,4] and micro-electromechanical systems (MEMS) [5,6]. Several studies have been dedicated to the design, characterization and comparative evaluation of straight-beam flexures and compliant mechanisms formed therewith, see e.g. Refs. [7,8,9]. Lobuntiu and Cullin [10] have recently introduced the two-segment circular-axis symmetric notch flexure and compared its in-plane compliance with that of the straight-axis counterpart. Parvari Rad et al. [11] have evaluated the spatial compliance of Circularly Curved-Beam Flexures (CCBFs), featuring an arc of a circle as a centroidal axis (see curve C in Fig. 1) and a rectangular cross-section (Fig. 2). In addition, Berselli et al. [12] have quantitatively compared CCBFs with straight-beam flexures in terms of maximum achievable rotation and selective compliance.

In any case, most of the aforementioned flexures have been conceived and applied to planar compliant mechanisms. Despite the practical relevance, investigations on compliant hinges specifically designed for spatial mechanisms are instead quite limited. One of the most important classes of spatial mechanisms is the spherical linkage. In spherical mechanisms, all points of the end-link are constrained to move on concentric spherical surfaces that are fixed with respect to the base. To date, only a limited number of works have investigated compliant joints specifically designed for spherical motion, as well as fully compliant spherical mechanisms. Smith [13] proposed compliant universal joints fabricated from circular leaf springs, which also provided axial translation for self-alignment applications. However, the proposed joints are affected by significant stress concentrations that limit their ranges of motion. Lobontiu et al. [14,15] investigated the two- and three-axis flexure hinges. The former consists of

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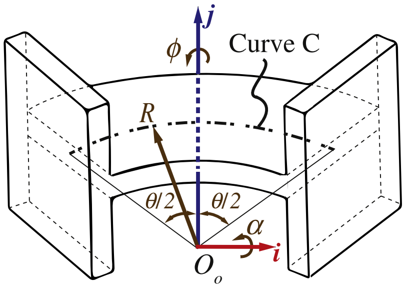

Fig. 1. Circularly curved-beam flexures.

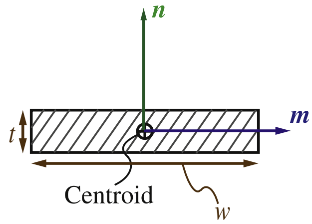

Fig. 2. Cross section properties of CCBFs.

two collocated notches that are cut perpendicular to each other; the latter consists of an axial-symmetric notch. In both cases, the resulting hinge features a small cross-sectional area and is prone to unintentional rotations or buckling even when loaded with small forces. Moon et al. [16] developed a compliant revolute hinge based on torsion beams of cross or segmented-cross type, and employed two of them, connected in series with orthogonal axes, to conceive a fully compliant universal joint. Later on, the ensemble of two universal joints of this kind has been proposed by Machekposhti et al. [17] to obtain a compliant constant velocity Double-Hooke's universal joint. Different authors [18,19] employed two in-series connected flexure notch hinges with orthogonal axes to conceive a fully compliant universal joint. Jacobsen et al. [20] employed three in-series connected lamina emergent torsional joints, with axes intersecting in a single point, to make spherical chains with three degrees of freedom (for compliant joints or mechanisms, the number of degrees of freedom is intended as the number of independent prevalent directions of motion). These spherical chains were then used to build a 3-RRR spherical parallel mechanism (R being a revolute joint). Callegari et al. [21] addressed the analysis and design of a 3-CRU spherical parallel mechanism with flexure hinges (C and U being cylindrical and universal joints respectively). Li and Chen [22] employed two circularly curved deformable segments

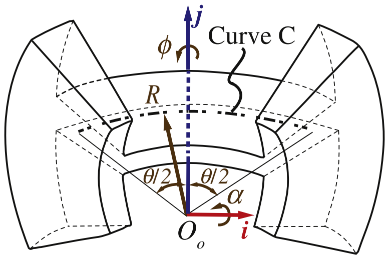

Fig. 3. Spherical flexures.

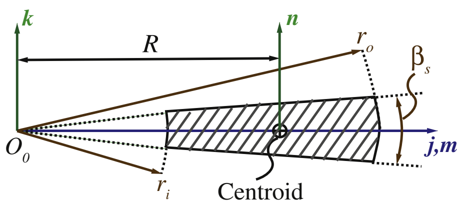

Fig. 4. Cross section properties of SFs.