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Compliant linear-rotation motion transduction element based on novel spatial helical flexure hinge

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ABSTRACT

In this paper, a novel sort of motion transduction elements (MTEs) with cylindrical helix structures are proposed for directly transforming a linear motion into a rotation. To characterize the elastic deformation behaviors of the MTEs based on the novel spatial helical flexure hinges (SHFHs), the finite beam based matrix modeling (FBMM) method is employed for calculation of its complete compliance matrix, and a transform ratio is defined to quantify its performances. Based on the FBMM method verified by the finite element analysis (FEA), the dependences of input/output stiffnesses and transform ratios on the dimensional parameters of the MTEs are theoretically revealed. By means of three-dimensional printing, a prototype of MTE is rapidly produced. Experimental test on it well verifies the working performance of the MTE as well as the effectiveness of the FBMM method.

1. Introduction

Compliant mechanisms (CMs) have been widely applied in a variety of fields due to their superior properties, including high resolution, ultrafine precision, compact structures, and friction free motions [1–3]. Currently, many types of flexure hinges were developed to construct the CMs in micro-machining systems [4,5], micro/nano manipulators [6,7], and micro/nano positioning stages [8,9]. For satisfying the ever-increasing working requirements, flexure hinges with improved performances were recently introduced. For example, the power-function-shaped flexure hinge [10] and the V-shaped flexure hinge [11,12] were developed to achieve higher moving precision, and a novel sort of exponent-sine-shaped flexure hinges with asymmetric structure featuring predominant rotation accuracy were also introduced [13].

Although various flexure hinges were developed, it is difficult for the existing hinges to directly obtain perfect angular motions from translational actuation motions. With the CMs, the conversion of translational–rotational motions often requires complex structures, resulting in degraded performance and oversized structures [14,15]. For example, several types of three degree-of-freedom (3-DoF) nano-positioning stages [15–17] or 6-DoF micro-manipulators [18] with rotational motions were recently developed, where leverage structures were adopted to convert translational motions to be desired rotational motions. Generally, it results in oversized structures, critically restricting some potential applications in terms of the compact structures and high response speed. Besides, the bad lateral shear stresses imposing on the piezoelectric actuators might damage the actuators. As discussed above, a sort of rotational flexure hinges, which can directly and effectively obtain perfect rotations, are very urgently need to be developed to facilitate designs of multi-DoF CMs with rotational motions.

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In the present study, a novel sort of motion transduction elements (MTEs) which are able to directly transform the linear motions into perfect rotations are proposed. Performances of the MTEs are thoroughly investigated by adopting a theoretical model as well as conducting experimental tests on a practical prototype.

2. Characteristics of the MTE

2.1. Structure of the spatial helical flexure hinge

A type of flexural hinge with coupling between its rotation and translation was mentioned in Ref. [19]. With this hinge, the simple linear links for motion conversion was lack of flexibility for adjusting system performance, namely stiffness, stroke, transform ratio, and dimensional sizes. Thereby, the novel cylinder helical links with more control parameters are employed here to add flexibility in the design process. The constructed spatial helical flexure hinge (SHFH) is illustrated in Fig. 1(a), and schematic of the kinematic principle is further illustrated in Fig. 1(b). As shown in Fig. 1(b), the red lines with arrows represent that the platforms can be movable in the corresponding directions. Assisted by the leaf spring flexure hinges (LSFHs) serving for directional restrictions as shown in Fig. 1(a), only translational motion along the z-axis direction can be generated as the input, while only rotational motion around the z-axis direction can be simultaneously achieved in the output end through the spatial deformations of the helical links. Since this study will mainly focus on the central substructure of the SHFH, called the motion transduction element (MTE), restrictions by the LSFHs will be ignored in the following analysis.

2.2. Compliance matrix of the MTE

To characterize the elastic deformation behavior of the MTE, a novel powerful finite beam based matrix modeling (FBMM) method without processing tedious integration operations is adopted for the compliance modeling [2,20,21]. Based on the Hooke's law, the relationships among the external loads $\mathbf{F}$, elastic deformations $\mathbf{\Delta}$ and compliance matrix $\mathbf{C}$ of the MTE, which can be expressed by:

$$\mathbf{\Delta} = \mathbf{C} \cdot \mathbf{F} \tag{1}$$

To obtain the compliance matrix $\mathbf{C}$, the helical links of MTEs are treated as a combination of finite micro-cylinders with serial connections as shown in Fig. 2, where o_i-$x_iy_iz_i$ denotes the local Cartesian coordinate of the i-th micro-cylinder. Following the small deformation theory in the Euler–Bernoulli beam frame, compliance matrix $\mathbf{C}_i$ of each micro-cylinder in its local coordinate o_i-$x_iy_iz_i$ can be found in [22,23].

Based on the FBMM method, the compliance matrix $\mathbf{C}$ of the MTE in its global coordinate system can be expressed by:

$$\mathbf{C} = \sum_{i=1}^{N} \mathbf{T}_i \mathbf{C}_i \mathbf{T}_i^{\mathrm{T}} \tag{2}$$

$$\mathbf{T}_i = \begin{bmatrix} \mathbf{R}_i & \mathbf{S}_i(\mathbf{r}_i)\mathbf{R}_i \\ \mathbf{O} & \mathbf{R}_i \end{bmatrix} \tag{3}$$

where $\mathbf{T}_i$ denotes the compliance transformation matrix of the i-th micro-cylinder, namely the location transformation matrix of the local coordinate system o_i-$x_iy_iz_i$ with respect to the global coordinate system o-xyz; N is the total amount of the divided micro-

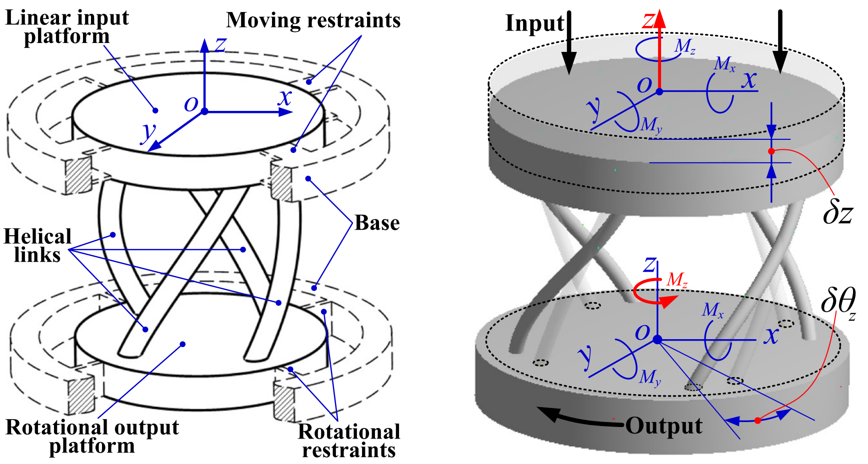

Fig. 1. The structure and kinematic principle of the proposed SHFH.