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Design of a spatial compliant translational joint

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This paper presents the design of a novel compliant translational joint with large stiffness ratio and small axis drift. The characteristics of compliant translational joints based on a leaf-spring type joint are investigated. Several types of constructions are analyzed. A novel three-dimensional compliant translational joint is proposed and a design analysis is conducted based on the parametric models. Subsequently, a design optimization is employed with the aid of finite element method. Then, a prototype of the optimized design is fabricated by 3D printing, and tests of specified properties are conducted. Comparisons of the experimental results and simulation results show that this new joint satisfies the design requirements.

1. Introduction

Conventional joints formed by rigid links, such as the revolute pair, the prismatic pair, and ball-and-sockets, are commonly used to connect mechanical parts. However, such joints may contain clearance between the pairing elements and lead to inaccurate positioning during motion. Furthermore, the relative motions between the pairing elements generate friction that results in wear and reliability issues. To overcome these drawbacks, design of the mechanism with compliant joints is proposed. Such mechanism usually consists of a series of rigid links connected by compliant elements and is designed to produce a prescribed motion when a force is applied. Since the mechanism is typically made from a monolith, there exits no clearance between rigid links. Thus, the use of compliant joints can eliminate the presence of friction, backlash, and wear in a mechanism.

Many types of mechanisms with compliant joints have been developed over the past decades. Smith [1,2] classified compliant joints in a mechanism into two types, namely, the notch-type joint and leaf-spring type joint. Jones [3,4] was the first researcher to utilize leaf springs to make a four-bar mechanism for translational motion. Plainevaux [5] derived the equations of nonlinear deformation for the cantilever of a leaf spring. Using these equations, the translational motion of the leaf-spring joint subject to dynamic loadings can be predicted. Paros and Weisbord [6] proposed a notch-type compliant joint, which later became a popular configuration used in the compliant mechanisms. Ragulskis et al. [7] applied static finite element analysis to notch-type joints. Their analysis results state that the range of motion of the notch-type joint is limited because of high stress concentrations occurring around the notch area.

Over the past few years, due to the advent of new technologies in optical measurement and/or precision machinery, compliant mechanisms with high precision are in demand for research institutes and industries. Goldfarb and Speich [8]

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proposed a revolute flexure joint in which the concept of stiffness ratio was established. The stiffness ratio is a useful index when comparing various compliant joints. Later, Awtar and Slocum [9] derived the equations for beam-based compliant structures where non-linearities arising from the force equilibrium conditions in a beam is approximated with moderate complexity. The authors mentioned that any undesirable motion in response to a primary motion is considered an error motion. The error motion is classified as a parasitic error if it occurs along the direction of constraint while it is considered a cross-axis error if it occurs along the direction of motion. Trease et al. [10] noted the necessity for the capacity of large displacement of compliant joints, and proposed compliant joints with large displacement, with three-dimensionally presented configurations. It was claimed that a better off-axis stiffness and lower axis drift (deviation from the line of motion) for a three-dimensional configuration over a planar configuration have been achieved. Gillespie et al. [11] studied a compliant haptic device using three-dimensional compliant rotational joints. Other than these, applications of compliant mechanisms may be found in the fields of MEMS [12–15], biological inspired mimetic [16], and precision engineering [17–20].

It is worth nothing that, except for [10] and [11], most literature that addresses the compliant mechanism design focuses on planar configurations. Since spatial joints are essential to the configuration of spatial mechanisms, it is necessary to explore more types of spatial joints for possible applications in spatial compliant mechanisms. Thus, the purpose of this paper is to study the characteristics of a few types of three-dimensional compliant translational joints and to propose a new one for design. In this work, the conceptual design of the spatial compliant translational joint is discussed. A new type of joint is then presented. The design parameters of the joint are identified and a design analysis is conducted to help identify which parameters are crucial for design. A design optimization is then performed based on these target parameters. Moreover, a prototype of the optimized design is fabricated and experiments for the stiffness are conducted. Finally, comparisons of the simulation and experimental results are performed to verify the design concept.

2. Conceptual design

2.1. Conventional flexure mechanisms with translational motion

Many flexure mechanisms that move linearly are built upon a four-link-like primitive construction where the rigid links are connected by leaf springs or a notched joint. The relative motion of the two rigid links, the frame and the moving part, arises from the deflection in the leaf spring or notched portion of the structure, as shown in Fig. 1. For the analysis of the flexure mechanism comprising notched joints, the pseudo-rigid-body model provided in [18] can be used to approximate the flexure mechanism as a traditional bar-connecting linkage and to obtain the motion of the moving part. However, this method cannot be applied to analyze a mechanism consisting of the leaf-spring elements whose non-linearity arises from the conditions when the loads and displacements in one direction may influence the stiffness properties of other directions. The force-displacement relations of the primitive flexure mechanism have been researched using both linear and nonlinear approaches [9]. One significant issue regarding the precision of the flexure mechanism is the off-axis displacement revealed in the primitive construction. To eliminate the axis drift in the primitive construction, Jones [3] proposed different types of structures consisting of series-connected or parallel-connected simple primitives. These series- or parallel-connected structures mainly use the characteristics of symmetry to compensate for the undesirable off-axis deformation in the mechanism.

To realize the advantages and drawbacks, the characteristics of flexure mechanisms that are constructed in series connection and in parallel connection will be investigated.

2.2. Flexure mechanisms in series connection

In a series connection, the flexure mechanism may comprise two or more simple translational primitives. The primitives may be linked in a line as shown in Fig. 2a or folded beneath a coupler link within the mother primitive as shown in Fig. 2b.

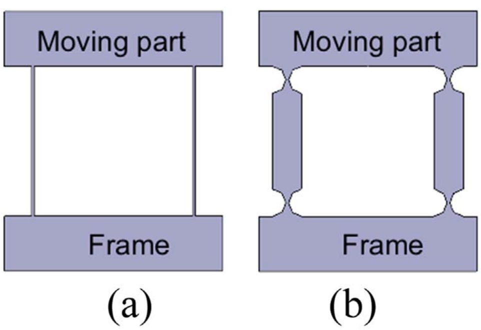

Fig. 1. Flexure joints (a) leaf-spring type (b) notch type.

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