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A tristable compliant micromechanism with two serially connected bistable mechanisms

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ABSTRACT

A tristable micromechanism with a bistable mechanism embedded in a surrounding bistable mechanism is developed. Three stable equilibrium positions are within the range of the linear motion of the mechanism. The proposed mechanism has no movable joints and gains its mobility from the deflection of flexible members. The tristability of the mechanism originates from the different actuation loads of the two bistable mechanisms. Finite element analyses are used to characterize the tristable behavior of the mechanism under static loading. An optimal design formulation is proposed to find the geometry parameters of the mechanism. Prototypes of the mechanism are fabricated by a simple electroforming process. The characteristics of the mechanism are verified by experiments. The force versus displacement curve of the mechanism exhibits the tristable behavior within a displacement range of 260 μm.

1. Introduction

Multiple passive stable equilibrium configurations enable the design of systems with both power efficiency and kinematic versatility while the actuators and control stay simple [1]. For example, multistable mechanisms can be used for multiple switching and optical networking [2]. With the concept of multistable mechanisms, a wide range of operating regimes or novel mechanical systems without undue power consumption can be created [1]. Substantial interest has focused on design of bistable [3–10], tristable, [11–16], and quadristable mechanisms [1,2,17].

In the regime of tristable mechanisms (TMs), Ohsaki and Nishiwaki [11] used a shape optimization approach to generate a truss-like TM. Due to the random nature of their design method, the number of structural members of the generated mechanism might be large. Su and McCarthy [12] synthesized a compliant four-bar linkage with three equilibrium configurations. A successful design relies on the fact that both kinematic and static constraints of their compliant mechanisms can be modeled in polynomial equations. Oberhammer et al. [13] proposed tristable mechanism actuated by electrostatic actuators. A large electrostatic force is required to avoid contact stiction between the structural members of their mechanism. Based on geometric symmetry, Pendleton and Jensen [14] demonstrated a tristable four-link mechanism. Their design has three mechanically stable positions gained through storage and release of elastic energy, not through friction or detents. Chen et al. [15] developed a tristable micromechanism based on the operation of a certain bistable compliant mechanism with soft spring-like behavior. When pulled in the opposite direction from the fabricated position, their mechanism exhibits the three stable equilibrium positions. Chen et al. [16] proposed a tristable mechanism which employs orthogonal compliant mechanisms to achieve tristability. Nonsymmetric designs may be needed to replace the symmetric configuration of their mechanism in order to reach a desired equilibrium position between the two possible deflected positions of the end-effector.

This paper describes a design of a compliant TM. The proposed TM has a curved-beam bistable mechanism embedded in another curved-beam bistable structure. Multi-stability is provided by buckling of curved-beam structures of the mechanism. The design

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concept of combining two bistable mechanisms has been reported by Han et al. [2], Chen et al. [17] and Oh and Kota [18], where the multistability originates from bistable behaviors of the mechanism along two orthogonal directions [2,17] or of a combined motion of two bistable rotational mechanisms [18]. The motion of the proposed TM is translational in a one-dimensional manner. Finite element analyses are carried out to evaluate the mechanical behaviors of the design. Prototypes of the device are fabricated using an electroforming process. Experiments are carried out to demonstrate the effectiveness of the TM.

2. Design

2.1. Operational principle

A schematic of the TM is shown in Fig. 1(a). A Cartesian coordinate system is also shown in the figure. The z axis completes the right handed orthogonal set. The mechanism consists of a shuttle mass, a guide beam, inner curved beams and outer curved beams. The inner curved beams clamped at one end by the shuttle mass and fixed at the other end by the guide beam acts similar to a bistable mechanism of curved beam type. The outer curved beams with one end clamped at the guide beam and the other end fixed at the anchor also behave similar to a bistable mechanism of curved beam type. The shuttle mass and the guide beam are employed to prevent the mechanism from twisting during operation, and are designed to be stiff. Furthermore, curved beams with large thickness in the z-direction could also be used to prevent twisting of the mechanism. Upon the application of a force F to the shuttle mass in the $-y$ direction, the outer curved beams deflect initially, increasing the strain energy. The compression energy in the outer curved beams increases to a maximum at a certain displacement of the mechanism, but then decreases as the mechanism snaps towards its second stable position, as shown in Fig. 1(b). As the TM deflects further, the bending energy in the outer and inner curved beams increases. While the compression energy in the inner curved beams increases to a maximum at a certain displacement of the mechanism, but then decreases as the mechanism snaps towards its third stable position, as shown in Fig. 1(c).

Vangbo [19] treated the snap-through behavior of a double-clamped curved beam using Euler's beam buckling theory [20]. He evaluated the bending and compression energy terms of his analytical solution, and found that bending energy is larger than compression energy when the beam is loaded initially; as the displacement of the beam increases, compression energy increases rapidly and bending energy decreases; after the event of snap-through of the beam, bending energy starts to increase again while the compression energy remains constant due to a constant stress normal to the cross-section of the beam.

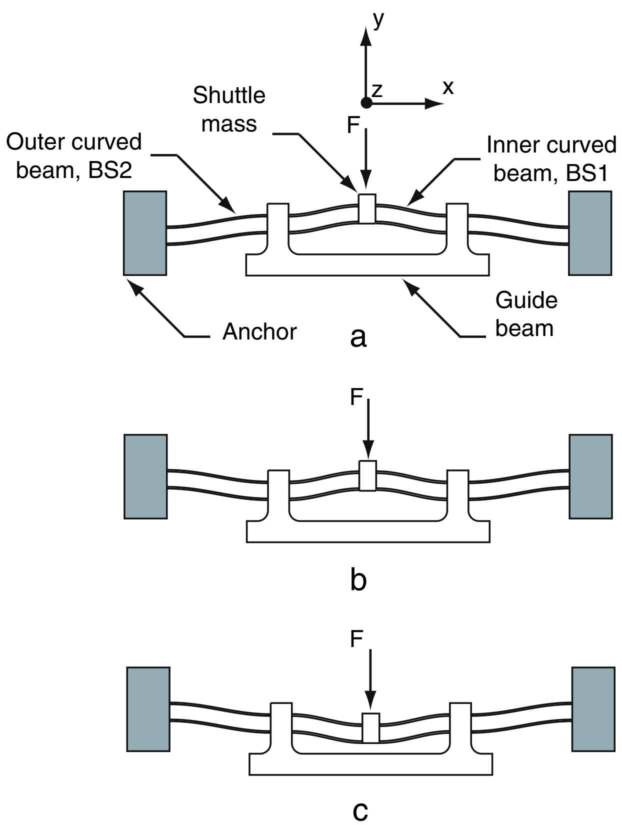

Fig. 1. Operational principle of the TM.