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A bistable rolling joint for multistable structures

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ABSTRACT

In this paper, a concept of using rolling joints for a multistable structure, which deforms elastically into a variety of cylindrical shapes, is presented. A bistable joint is obtained by modifying the geometry of a rolling hinge. The proposed concept can hold the stable state without any continued actuation. Then detailed mathematical derivations are carried out to obtain the wire tensions and joint resultant moment during the motion, which are used to compute the external action that should be applied to move the joint. The effects of some geometric parameters on the mechanical behavior are also investigated. The results show that higher values of the wire tension and joint resultant moments can be obtained by increasing the side included angle φ or the radius of wire wrapped circles R. Moreover, the pretension of wires in the stable configuration also increases the wire tension and the joint resultant moment.

1. Introduction

A novel concept of multistable structures, which has several different configurations of stable equilibrium without any external loads, is introduced for morphing structures. The proposed structure, which is inspired by the multistable plate structures given in Ref. [1], takes up a variety of cylindrically curved shapes.

Morphing structures are currently receiving significant interest from the engineering community [2,3], especially for the application to flow control methodologies, active jet inlets and adaptive, reconfigurable reflector surfaces. Many concepts for morphing structures need the continuously powered actuators to hold the configuration of stable equilibrium [4–7]. An alternative concept for morphing structures uses discrete parts articulated around a number of linkages, which is able to hold the stable state without any continued actuation. One example of this concept is an adaptive plate based on double-layer Kagome lattice [8–10]. The structures have two flat face-sheets, which are held at a distance by an active back-plane comprising of a Kagome truss, capable of changing the shape of a solid face. Curvature is imparted to the structure by extending or contracting a number of actuators.

Variable geometry truss (VGT) is an assembly of bars connected to each other by pin joints at the ends. As the name suggests, it has variable geometries. The difference between VGTs and common spatial trusses is that the length of the struts of VGTs can be changed. Thus, the configurations of VGTs are determined by the length of the struts. Generally, a VGT is a statically and kinematically determinate structure. This is because that the statically determinate structure is accommodated by a change in geometry, rather than by inducing internal stresses in the structure when the length of any bar is change. Similarly, kinematically determinate structures are adopted in order to that the structure has a unique configuration. The main longerons can be replaced by linear bistable elements to control the configuration of the VGTs [11]. A bistable structural element, which is achieved by material selection, such as by the snap-through behavior [12], has attracted considerable research interests in recent years, especially at Massachusetts Institute of Technology [13–15], Johns Hopkins University [16–18] and University of Cambridge [11,19]. Santer and Pellegrino [1] proposed a compliant plate structure with the concept of VGTs. They attached the compliant plate to a series of inclined thin plates. Then the length changing of a bistable element, which is connected the inclined thin plates, has the effect of bending the plate.

A multistable rolling joint, as shown in Fig. 1, has been studied by Halverson et al. [21], Cai and Feng [22], Jeanneau et al. [23]. Assuming that the two prisms are essentially rigid and the cables are flexible, the joint can be moved from one configuration to the other around an axis that passes through the common vertex of the bases, which is shown in Fig. 1. This multistable rolling joint has been used in multistable plate structures by Cai and Feng [22]. However, it is easy to see that a large number of multistable rolling joints are need to built a variable geometry structure, the number

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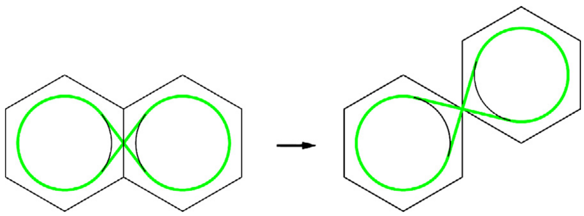

Fig. 1. Concept of multistable rolling joints.

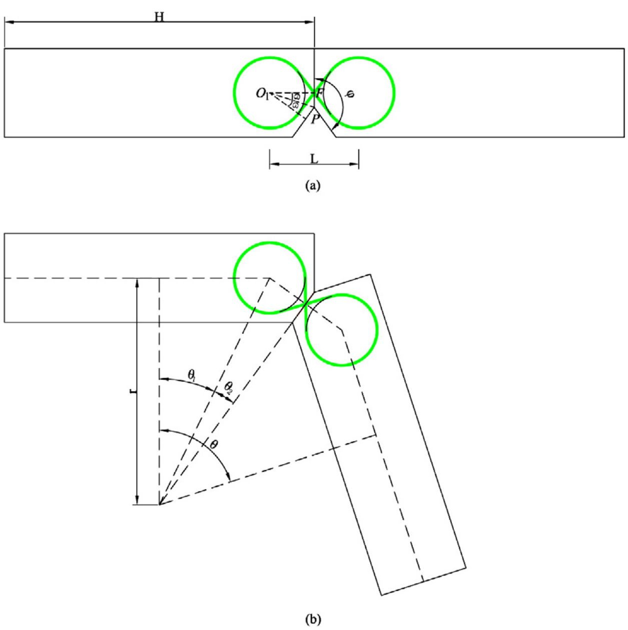

Fig. 2. Concept of bistable plate structures.

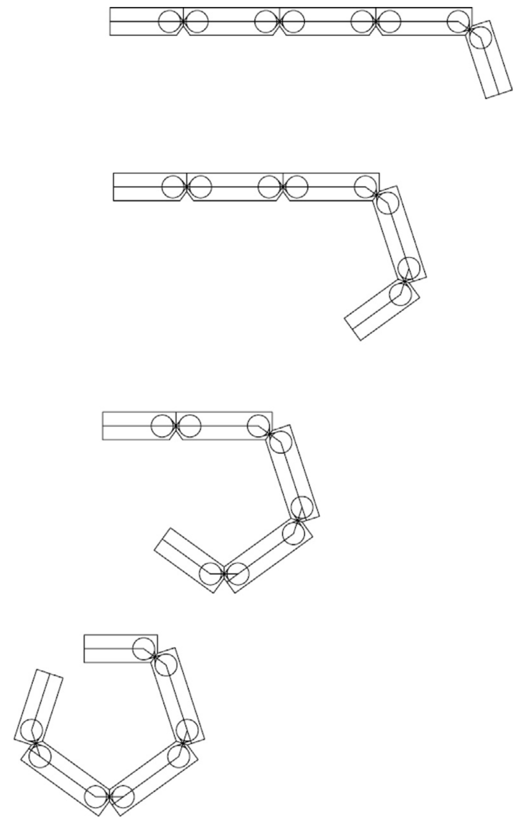

Fig. 3. Movement of multistable plate structures.

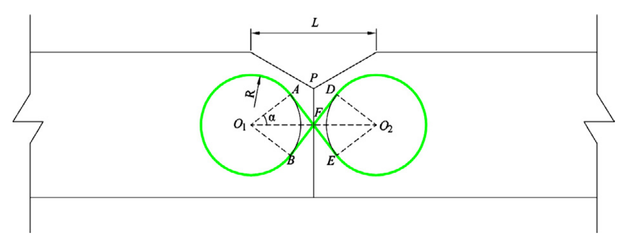

Fig. 4. Geometric model for a stable configuration.

of degrees of freedom (DOFs) for the system are very big. Not only does a large number of DOFs make the inverse kinematics of the system more complex, moreover, complex (and expensive) feedback control systems are still present. One way around this problem is to construct a variable geometry structure with bistable rolling joints. Moreover, only the basic mechanical behavior of the rolling joints has been studied by Cai and Feng [20]. The influence of the geometry parameters and the prestress of wires are not considered.

The paper is arranged as follows. In Section 2, the concept and the kinematic behavior of multistable plate structures are discussed in a general form. In the following section, the mechanical behavior of the bistable joints is studied. This section also provides the required characteristics of the moment-rotation relationship of bistable joints, which are able to hold a given compliant plate in a deformed configuration. The results are discussed in Section 4. Finally, Section 5 concludes the paper and suggests the research direction for future work.

2. Structural concept

The multistable plate structure should have many stable configurations including: initial flat stable configuration, intermediate stable configurations that consist of flat and curved regions, and final cylindrical stable configuration. Also the structure can hold these stable shapes without any external actuation.

Fig. 2 shows the concept of the plate for multistable structures. The cross section of the prism plate with the bistable rolling joints is given in Fig. 2(a), which is in a flat configuration. When the joint rotates by a known amount to the other stable state, the plate is in a curved configuration, which is shown in Fig. 2(b). Although the proposed concept requires a chain of the plate element with bistable rolling joints, the two adjacent units shown in Fig. 4 fully capture the behavior of the whole structure. This is because the curvature imparted to the structure by a bistable rolling joint is localized to the region under the adjacent two plates. The sequential movement of the multistable structures with five plates is shown in Fig. 3.

The section length of the plate is H, the distance between the centers of the circle for the wrapped wires in the stable configuration is L. If the length between the points F and P is S, the angle ω as shown in Fig. 2(a) is

$$\omega = \arctan\left(\frac{S}{L/2}\right) \tag{1}$$

Then the included angle φ of the two sides of the rolling joints shown in Fig. 2(a) is

$$\varphi = 2(\pi - \omega) \tag{2}$$

Thus the included angle θ of the adjacent plate in the curved configuration as shown in Fig. 2(b) is

$$\theta = 2(\pi - \phi) = 4\omega \tag{3}$$