Sensors and Actuators A 268 (2017) 72–82

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A novel fully compliant tensural-compresural bistable mechanism

Qi Han, Kaifang Jin, Guimin Chen*, Xiaodong Shao

School of Electro-Mechanical Engineering, Xidian University, Xi'an, Shaanxi 710071, China

ARTICLE INFO

Article history:
Received 21 April 2017
Received in revised form 4 October 2017
Accepted 4 October 2017

Keywords:
Bistable mechanism
Tensural segment
Compresural segment
Beam constraint model
Chained beam constraint model

ABSTRACT

Bistable mechanisms, which can maintain two distinct positions without power input, have been widely used for harvesting vibration energy, constructing metamaterials, sensing threshold acceleration, and achieving adaptable damping. In this work, we propose a novel configuration of fully compliant bistable mechanisms called tensural-compresural bistable mechanisms (TCBMs), in which both tensural segments (compliant segments that are subject to combined tensile and bending loads) and compresural segments (compliant segments that are subject to combined compressive and bending loads) are employed. The combination use of tensural and compresural segments makes TCBMs much easier to be tailored for different design requirements. Although compresural segments are incorporated, potential problems associated with buckling can always be avoided by using compresural segments with smaller slenderness as compared to the tensural segments. To facilitate the design of TCBMs, two kinetostatic models are developed by using the beam constraint model and the chained beam constraint model, respectively. Several TCBM designs accompanied with a prototype test are presented to demonstrate the feasibility of the new bistable configuration and the use of the two kinetostatic models.

1. Introduction

Bistable mechanisms, which can maintain two distinct positions without power input [1], have been widely used for state switching [2–5], vibration energy harvesting [6,7], nonvolatile shock detecting [8], mechanical memory [9], metamaterials construction [10], tristable and quadristable mechanisms synthesis [11–14], and overload protection [15]. There are a variety types of compliant bistable mechanisms, for example, the compliant four-link bistable mechanisms [16,17], the Young bistable mechanisms [18,19], the compliant bistable Sarrus mechanisms [20], bistable mechanisms employing initially straight beams [21,23–26,22,27,28], and bistable mechanisms utilizing curved beams/plates [32,34,30,33,31,29].

In most of the bistable mechanisms, the compliant segments are designed to be subject primarily to combined compressive and bending loads [21,22,32,34,33,31,29]. These segments will be referred to as compresural (short for compressive flexural) segments hereafter. Interestingly, Masters and Howell [23] first used compliant segments loaded in tension and bending instead of compresural segments to create a fully compliant bistable mechanism called self-retracting fully compliant bistable mechanism (SRFBM). Compliant segments that are loaded in tension and bending are called tensural (short for tensile flexural) segments [23]. Because tensural segments are loaded in tension, buckling failure is no longer a concern [38,39], and non-symmetric switching modes can be avoided [34,36,37,35]. A tensile load always results in a moment that counteracts to the bending deflection of a compliant segment, thus tensural segments are suitable for designing small displacement bistable mechanisms (to lower power assumption for switching). Besides SRFBMs, another two types of bistable mechanisms employing tensural segments were proposed, which are double-tensural fully compliant bistable mechanisms (DTBMs) [24] and fully compliant tensural bistable mechanism (FTBMs) [25], respectively. To facilitate the design of DTBMs, two kinetostatic models were developed [40]. However, design of these bistable mechanisms is still nontrivial because the bistable behavior requires that the strain energy due to tension dominates over the strain energy due to bending in the tensural segments, which often leads to tensural segments designs that are too thin to be realized due to the practical limitations of stress and fabrication constraints [41].

In this work, we propose a novel configuration of fully compliant bistable mechanisms called tensural-compresural bistable mechanisms (TCBMs), in which both tensural segments and compresural segments are employed, as illustrated in Fig. 1. TCBMs significantly extend

* Corresponding author.
E-mail address: guimin.chen@gmail.com (G. Chen).

https://doi.org/10.1016/j.sna.2017.10.012
0924-4247/

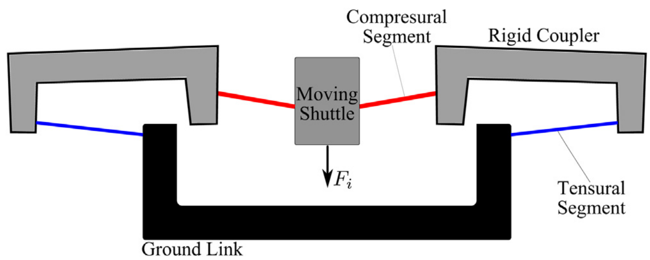

Fig. 1. A fully compliant tensural-compresural bistable mechanism.

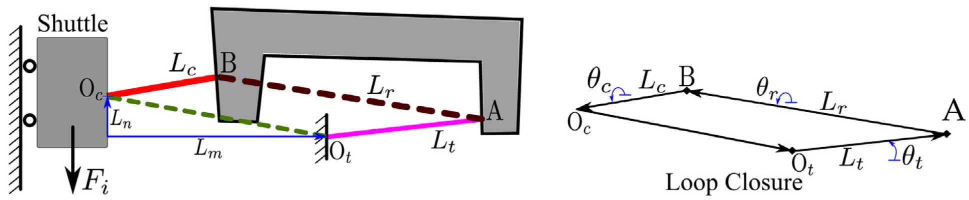

Fig. 2. Geometrical parameters of a TCBM (O_tA, O_cB and AB are corresponding to the tensural segment, the compresural segment and the rigid coupler, respectively).

the available design space of bistable mechanisms. The combination use of tensural and compresural segments makes TCBMs much easier to be tailored for different design requirements. Although compresural segments are incorporated, potential problems associated with buckling can always be avoided by using compresural segments with smaller slenderness (the ratio of length to thickness) as compared to the tensural segments. To accurately capture the nonlinear deflections of the tensural and the compresural segments in TCBMs, the Beam Constraint Model (BCM) [42–44] and the Chained Beam Constraint Model (CBCM) [45,46] are employed (which are more robust than the elliptic integral solutions [47,48]), based on which two kinetostatic models are developed to facilitate the design of TCBMs.

In the following, Section 2 briefly introduces the main parameters of a TCBM, Section 3 formulates the two kinetostatic models for it, and Section 2 provides several TCBM designs accompanied with a prototype test to demonstrate the feasibility of the new bistable configuration and the use of the two kinetostatic models.

2. Tensural-compresural bistable mechanisms (TCBMs)

Because a TCBM is symmetric with respect to its vertical centerline, only half of it is considered. Fig. 2 shows the right half for a TCBM, in which three rigid links (the coupler link, the grounded link and the mobile link) are connected by two compliant segments and form a closed loop. This design configuration ensures that the right compliant segment to tensile-force dominated loads (tensural segment), while the left compliant segment is subject to compressive-force dominated loads (compresural segment). The lengths of the tensural segment and the compresural segment are denoted as L_t and L_c, respectively. The slenderness (L/t) of the compresural segment should be smaller than that of the tensural segment to reduce the risk of buckling. Their corresponding in-plane and out-of-plane thicknesses are H_t, W_t, H_c and W_c. I_t and I_c represent the flexural rigidities, which are defined as

$$I_t = W_t H_t^3/12, \quad I_c = W_c H_c^3/12 \tag{1}$$

The length of the rigid coupler is L_r. By placing the global coordinate frame (XOY) with its Y-axis along the opposite travel direction of the shuttle, the initial angles of the tensural segment, the compresural segment and the coupler measured with respect to the X-axis are θ_t, θ_c and θ_r, respectively. Then we have the following expressions for L_m and L_n:

$$L_m = -L_t \cos\theta_t - L_r \cos\theta_r - L_c \cos\theta_c \tag{2}$$

$$L_n = L_t \sin\theta_t + L_r \sin\theta_r + L_c \sin\theta_c \tag{3}$$

It should be noted that L_m is always positive but L_n can be either positive or negative. A negative L_n indicates that point O_c is below point O_t with respect to the XOY coordinate frame at the as-fabricated (undeflected) position. The dominating parameters of TCBMs include L_m, L_n, L_t, L_c, H_t, H_c, θ_t and θ_c.

For the purpose of simplifying the kinetostatic modeling, the local coordinate frame for the tensural segment L_t is established with the origin placed at its fixed end O_t and the X_t-axis along the length direction of its undeflected configuration ($X_tO_tY_t$). When deflected, this segment is subject to a horizontal force F_{xt}, a vertical force F_{yt} and a moment M_{zt} at its tip (point A), and the corresponding tip deflections are denoted by axial deflection Δ_{xt}, transverse deflection Δ_{yt} and tip slope $\Delta\theta_t$, all measured with respect to $X_tO_tY_t$. Similarly, for compresural segment L_c, the local coordinate frame $X_cO_cY_c$ is established with the origin placed at its end attached to the shuttle (point O_c), and the X_c-axis along the length direction of its undeflected configuration. This segment is subject to tip loads F_{yc}, F_{xc} and M_{zc} at point B, and the corresponding tip deflections are denoted as Δ_{xc}, Δ_{yc}, and $\Delta\theta_c$, all of which are measured with respect to $X_cO_cY_c$ (Fig. 3).

3. Kinetostatic modeling

Modeling the nonlinear deflections of the tensural and the compresural segments is critical to the development of the kinetostatic model for TCBMs. Model I employs the beam constraint model (BCM) [42] for these segments because it accurately captures the relevant geometric nonlinearities in the intermediate deflection range (10% of the segment length) and the moderate axial-force range (±10 for