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Research paper

Design of a crab-like bistable mechanism for nearly equal switching forces in forward and backward directions

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ABSTRACT

A compliant bistable mechanism with a crab-like structure for nearly equal switching forces in the forward and backward directions is developed. It consists of four crab-leg-like beams and a shuttle mass. The crab-leg like beam gives more design freedom than straight beam or curved beam seen in the traditional bistable mechanisms. This design flexibility is exploited here for the design of a bistable mechanism with nearly equal switching forces in the forward and backward directions. Key parameters affect the force-displacement characteristics of the bistable mechanism are identified. The performance of the mechanism is confirmed by experiments. Such a mechanism can be applied in nonvolatile memory devices with two logical levels “1” and “0” assigned to the two stable states which are separated by nearly equal switching forces in back and forth directions.

1. Introduction

Given the advantages of ease of open-loop control, zero power consumption to stay in stable equilibrium states and insensibility to noise [1], compliant bistable mechanisms (CBMs) have potential applications in nonvolatile memory elements [2], micro switch or micro relays [3], projection displays [4], threshold accelerometers [5], etc. In the aspect of design of CBMs, force-displacement (f-d) and energy-displacement relations are often considered as the design metrics. A CBM with nearly equal switching forces in back and forth directions (symmetric force output) can be applied in nonvolatile memory devices with two logical levels “1” and “0” assigned to the two stable states. The symmetric force output of the CBM can be applied in threshold accelerometers to achieve two sensing directions along the sensing axis. For bistable micro switches driven by comb-drive type actuators, force symmetry may be advantageous since the force developed by the actuator is proportional to the applied electric potential which may be limited by the conventional complementary metal-oxide-semiconductor (CMOS) technology.

Force asymmetry with respect to the sign of deflection of CBMs is usually present in the literatures [6–12]. The traditional straight beam type design [6, 9, 13] and curved beam type design [10–12] restrict the degree of freedom in design of CBMs and often render them with unequal switching forces in the forward and backward directions during their operation. Liu et al. [14] reported a CBM with symmetric force output based on pre-shaped beams. A pre-load operation is necessary to bring their structure into initial configuration. Another approach to obtain symmetric force behavior of CBMs is by pre-compression of slender beams [15]. The additional control scheme for the amount of compression introduces design complexity.

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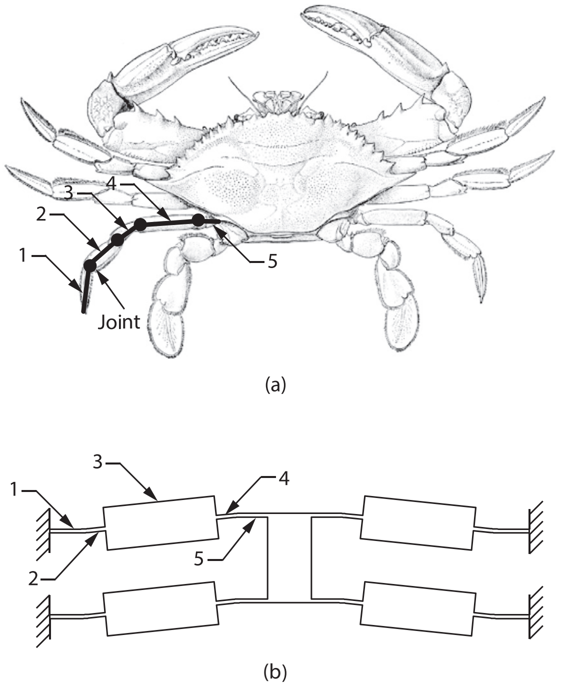

Fig. 1. Schematic of (a) a typical crab and (b) a crab-like CBM.

The straight beam or curved beam of the CBMs can be sectioned into several segments in order to have the design flexibility to achieve required bistable characteristics. The number and the configuration of the segments have great influence on the switching forces and switching modes [16]. Key configurations of the sectioned segments should be investigated to decrease design complexity and ease the design process. Methods based on optimization approaches [17], analytical equations [18] or inverse static analyses [19] can then be utilized to design the CBMs with specific f-d characteristics. Valentini and Pennestrì [20] developed an analytical model to compute the stiffness of flexure hinges for synthesis of flexure joints. Verotti [21] derived analytical expressions to determine the position of the center of rotation of flexures to assist the design of compliant mechanisms. A bistable mechanism with equal switching forces will also benefit design of tristable mechanisms and multistable mechanisms [22]. Chen et al. [22] utilized a bistable mechanism for providing latching forces, in which large enough latching forces are required for both forward and backward motion.

In this investigation, a crab-like CBM for symmetric force output with respect to the sign of deflection is developed. Fig. 1(a) and (b) shows a crab and a crab-like CBM, respectively. The beams of the CBM are similar to the walking legs of the crab in shape. The five-segmented beams of the CBM gives more design freedom. The force symmetry of the CBM is sought by adjusting the lengths of the five sections of the beam and the inclination angle using an optimization approach. Finite element analyses are utilized to evaluate the f-d characteristics of the CBM. Key design parameters are recognized for efficient design of the CBM with symmetric force output. Experiments are carried out to verify the force symmetry of the CBM.

2. Design

2.1. Operational principle

Because the body and leg movements of crabs are almost entirely in the same plane and the high agility of their legs, crab-like mechanisms are well-suited for design of planar motion mechanism [23]. Fig. 1(a) is a sketch of a crab. One of its legs can be dissected into five sections as numbered in the figure. This five sectioned geometry can be mimicked to develop a mechanism for motion generation and control. A schematic of a crab-like CBM with four five-section beams and a shuttle mass is shown in Fig. 1(b). The analogy between the crab leg and the beam of the CBM is indicated by the numbers shown in Fig. 1(a) and (b), respectively. It is assumed the CBM remains parallel to the underlying substrate. Fig. 2(a) is a schematic of the CBM where a shuttle mass is supported by four beams. One end of the beams is fixed to the substrate. A Cartesian coordinate system is also shown in the figure. Each beam consists of one stepped slanted section and two horizontal sections. As shown in Fig. 2(a), the mechanism is designed to move in the x direction when a force F is applied quasistatically at the center of the shuttle mass. Fig. 2(b) is a schematic of a quarter model of the mechanism. The left end of the beam of the quarter model can be represented as a fixed boundary condition. The symmetric plane of the quarter