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Design considerations of a large-displacement multistable micro actuator with serially connected bistable elements

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ABSTRACT

In this work we report on a finite element modeling and design methodology, fabrication and characterization of a large-displacement low voltage multistable micro actuator with an integrated electrostatic comb drive transducer. The compliant suspension of the device incorporates multiple serially connected bistable arch-shaped beams and exhibits controllable sequential snap-through buckling under an increasing actuation force. The device can be considered therefore as an example of a compliant multistep structure. The device is also distinguished by its ability to remain in several different stable configurations at the same actuation voltage while the force–displacement characteristic of the suspension can be tailored by changing the geometry parameters of the flexures. A model built using the shallow arch approximation along with a nonlinear finite element analysis were used in order to study the influence of the suspension architecture on the stability limits of the structure and for evaluation of design parameters of the actuator. Bistable and multistable devices were fabricated by a Deep Reactive Ion Etching (DRIE) based process using silicon-on-insulator (SOI) wafers. Experimental results, which are consistent with the model predictions, demonstrate that the compliant multistep devices exhibit improved lateral stability and consequently larger stable displacements compared to the conventional comb drive actuators. Stable displacements up to 80 μm at a voltage of 30 V were registered in the experiments while three snap-through and snap-back events took place during loading and unloading, respectively. Our computational and experimental results show that the suggested device has clear functional advantages and can be efficiently used in applications including switches, threshold inertial sensors, variable optical attenuators as well as in micro-and nanomechanical logical elements.

1. Introduction

Bistability and multistability, namely, the existence of two or several different stable configurations at the same loading, is an intrinsic feature of many mechanical structures. This behavior typically originates from the geometric nonlinearity of the structure resulting in a non-monotonous stiffness–displacement characteristic. One of the most common examples is a flexible arch loaded by a transverse force [1–3], Fig. 1(a). This structure is bistable in the interval of the force between the snap-back (release) and snap-through values (see Fig. 1(b)). The analysis of structures liable to snap-through buckling, mainly arches, frames, cylindrical panels and spherical caps, is a well-established topic in structural mechanics [1–5].

In microsystems, bistability is beneficial in many applications including electrical [6,7] and optical [8] switches, optical attenuators [9], inertial sensors [10], light processing devices, tactile displays [11] and nonvolatile memories [12–14]. A large variety of architectures and operational principles of bistable micro devices were reported. Elastic suspensions in bistable micro devices were typically realized as chevron-shaped rigid links combined with compliant pseudo-hinges [7,15–17]. Designs incorporating fully compliant suspensions realized as initially curved or tilted beams were reported as well ([6,8,18–23]). Actuation was done manually by probe [16,22,24] or provided by thermal [18,19,23,24] electrostatic comb drive [15,20,21,25] or magnetic [8,26] transducers. Note that in all cases listed above the actuation force was independent on the actuator's displacement and the nonlinearity was purely of a mechanical nature. Significant attention was paid to the theoretical and experimental analysis of static and dynamic behavior of fully compliant bistable micro beams [24–33]. Note that recently reported electrostatically actuated bistable devices may exhibit both mechanical snap-through and electrostatic (so

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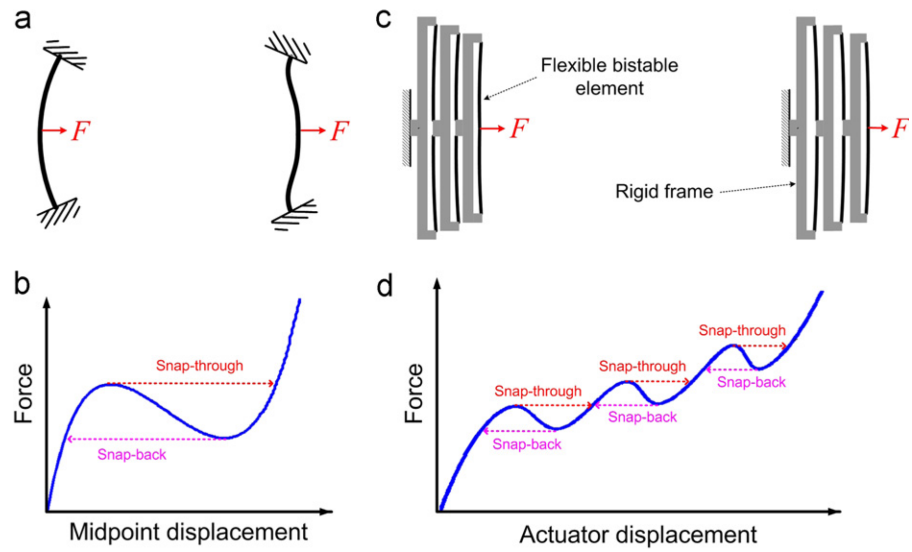

Fig. 1. An arch loaded by a transverse force in a pre-buckling and post-buckling configuration (a) and schematics of a corresponding limit point buckling curve (b). Operational principle of the device-schematics of a device incorporating multiple serially connected bistable beams (c) and a generic limit point buckling curve (d).

called pull-in) instabilities [28–33]. The reason is that these devices combine both geometric mechanical nonlinearity originating in an initially curved shape of the beams and electrostatic softening nonlinearity associated with the electrostatic force that reduces the effective stiffness of the structure.

The concept of the device considered in this work is based on a serial connection of multiple mechanically bistable curved beams, each attached to a rigid frame, Fig. 1(c). Since different elements of this chain of bistable elements are designed to exhibit a dissimilar snap-through force, a sequence of snap-through events takes place under an increasing force applied to the last element, as shown in Fig. 1(d). The force–displacement curve of the structure contains several stable branches and the device is actually a fully compliant multistep structure. By adjusting the geometrical parameters of the curved beams forming the compliant suspension, the shape of the limit point buckling curve can be tailored in a wide range. For appropriately chosen parameters, the device may remain in several different stable configurations at the same actuation voltage. The ability to tailor the stability properties of the actuator is one of the distinguishing features of the device under consideration.

It should be noted that the idea to obtain a multistable behavior by means of serial connection of bistable elements is not new. Results of theoretical investigation of the static and dynamic behavior of chains of bistable elements as well as wave propagation in these systems (often viewed as waves of phase transition) were largely reported in applied mechanics literature (e.g. see [34–40]). Possible design realizations, design methodology and synthesis of multistable compliant mechanisms using combinations of bistable elements were discussed in [41]. In microsystems, reported multistable devices mainly incorporated mechanical latching (ratchet-type) elements (e.g., see [9,42]). Tri-stable microfabricated device based on a bi-directional (double tensural) operation was reported in [43]. The device included an assembly of oblique beam-like suspension springs and was operated mechanically by a micro manipulator. A tri-stable mechanism with bi-directional operation actuated by a electroactive polymeric actuator ("aritifical muscle") was reported recently in [44]. The fully compliant multistable device with the suspension incorporating serially connected bistable elements and with integrated electrostatic actuation was first reported in [45].

In this work we present the design, fabrication and characterization of the device. The main focus is on the finite element

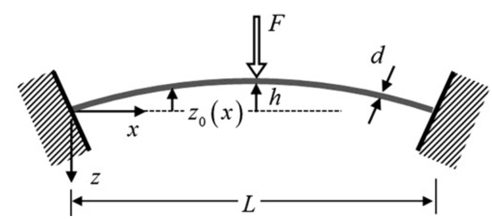

Fig. 2. Model of a curved beam.

modeling and design aspects of the device development. In the next section, the model of the generic device based on a shallow curved beam serving as a single bistable element of the suspension is considered. Main features of the device stability behavior are illustrated and the applicability of the shallow beam model is discussed. Next, several design configurations of the device are introduced and results of finite element analysis of these configurations are presented. We show that the lateral (pull-in) instability of the electrostatically actuated structure represents the main design challenge in this kind of device and requires careful design and finite element modeling. Finally, we present the results of the device fabrication and characterization illustrating the feasibility of the suggested approach. Conclusions summarize the main findings of the work.

2. Computational model

2.1. Curved beam

In order to provide an insight into the influence of different parameters on the stability properties of a curved beam and choose the design parameters, the most suitable for the control of the multistable behavior, we first consider a model of a single initially curved beam, Fig. 2.

We consider a flexible, initially curved, prismatic micro beam of length L, of a rectangular cross-section of area $A=b\times d$ and second moment of the area $I_{yy}=bd^3/12$. The initial shape of the beam is described by the function $z_0(x)=h\psi_0(x)$ (for convenience it is considered positive in the negative direction of the z-axis, Fig. 2) where h is the initial elevation of the central point of the beam about its ends and $\psi_0(x)$ is a non-dimensional function such