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Latching in bistable electrostatically actuated curved micro beams

Lior Medina[a,*], Rivka Gilat[b], Slava Krylov[a]

[a] *Faculty of Engineering, School of Mechanical Engineering, Tel-Aviv University, Ramat Aviv 6997801, Israel*
[b] *Department of Civil Engineering, Faculty of Engineering, Ariel University, Ariel 44837, Israel*

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ABSTRACT

Curved beams subjected to transverse force may exhibit latching phenomena, namely remain in the buckled configuration under zero force. In this study we investigate the latching in bistable electrostatically actuated initially curved and prestressed beams. The analysis is based on a reduced order (RO) model resulting from the Galerkin decomposition with buckling modes of a straight beam as base functions. Criteria for the existence of latching are derived in terms of the beam geometric parameters and axial load. Two conditions are formulated: The necessary criterion establishes the appearance of latching in the case of a symmetric snap-through, and the sufficient condition assures the existence of latching in the presence of symmetry breaking. The results provided by the RO model are compared to results obtained by direct numerical analyses. Furthermore, the dynamic behavior of curved beams prone to latching, and actuated by a suddenly applied electrostatic force of finite duration, is numerically studied. The dependence of the response on the loading parameters and the damping is presented through maps. These maps indicate the conditions required for trapping the beam at a secondary stable latching point, which is either accessible or inaccessible under quasi-static actuation. In addition, dynamic release of a latched beam is presented without the usage of an additional electrode, usually used for generating an opposite quasi-static release force.

1. Introduction

Micro and nano devices incorporating bistable structural elements such as beams are designed to exploit the fact that they possess two stable configurations at the same actuation force. The transition between two stable states in these structures is commonly referred to as snap-through buckling. The behavior of beams liable to snap-through, under prescribed deflection-independent “mechanical” loads was intensively investigated (e.g. Das & Batra, 2009a; 2009b; Krylov, Ilic, & Lulinsky, 2011; Pane & Asano, 2008; Park & Hah, 2008; Pi, Bradford, & Uy, 2002; Qiu, Lang, & Slocum, 2004; Saif, 2000; Simitses, 1989; Simitses & Hodges, 2006; Villagio, 1997; Zhang, Wang, Huang, & Li, 2007).

In recent years, along with the increasing interest in MEMS, the influence of the electrostatic force on the beam snap-through behavior drew special attention. Mainly due to its nonlinear, configuration dependent nature, which induces instabilities such as the electrostatic pull-in, where the beam collapses to the electrode. Static and dynamic snap-through and pull-in behavior were extensively investigated by various analytical, numerical and experimental approaches for the case of

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[*] Corresponding author.
E-mail address: liormedi@post.tau.ac.il (L. Medina).

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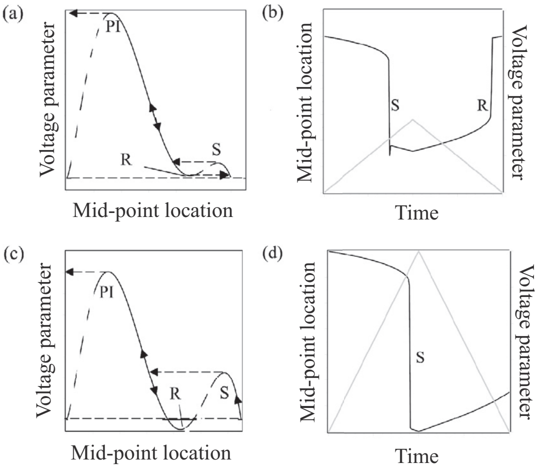

Fig. 1. Buckling curves of two different bistable beams (a)(c) and their respective responses (time history) (b)(d) to a triangle quasi-static signal. (a)(b) represent a bistable element without latching and (c)(d) represent a bistable element with latching. *S, R* and *PI* correspond to the snap-through, release and pull-in limit points. Arrows along the curve represent the beam movement along the equilibrium branch under quasi-static load. Solid and dashed lines conform to stable and unstable branches, respectively. Dashed line represents the beam schematic movement upon reaching the snap-through, pull-in and release points. The solid black line in the time history represents the beam response, and the thick solid gray line represents the time dependent actuation voltage. Dashed black line represents zero voltage.

curved beams. Notable past works examined the effects of initial curvature (Ghayesh, Farokhi, and Amabili, 2013; Krylov, Ilic, Schreiber, Seretensky, and Craighead, 2008; Medina, Gilat, Ilic, and Krylov, 2014a; Medina, Gilat, and Krylov, 2012; Ouakad and Younis, 2010 and references therein), imperfection (Farokhi and Ghayesh, 2016 and references therein), and an axial force (Ghayesh and Farokhi, 2015; Medina et al., 2014a; Medina, Gilat, and Krylov, 2013; 2014b and references therein) on bistability of beams.

Beams exhibiting bistability may also exhibit a latching phenomenon, namely the ability to remain in the second stable state under zero load. As a result, quasi-static snap-back of such beams can only be achieved under a force in the opposite direction. An example of such a response is shown schematically in Fig. 1, where two bistable beams with different parameters are subjected to a triangular quasi-static actuation voltage. With increasing load, both beams move along the initial equilibrium branch until a snap-through to the second stable branch occurs. Since the load is still increasing, both beams continue to move along the secondary stable branch. When the force starts to decrease, the movement of both beams on the secondary stable branch changes direction towards the release point. However, while the beam presented in (a) snaps back to its initial equilibrium branch upon reaching the release voltage, beam (c) remains at the second equilibrium branch, at a point which corresponds to zero voltage. That zero load point is the latching point. Consequently, latching occurs when the release point voltage is zero or negative.

Latching can be used for a variety of applications, such as RF switches (Que, Udeshi, Park, & Gianchandani, 2004), locking mechanisms (Qiu, Lang, Slocum, & Weber, 2005), and threshold accelerometers (Hansen, Carron, Jensen, Hawkins, & Schultz, 2007). The first example, presented in Que et al. (2004), describes a bistable truss used to minimise the power consumption of an RF switch. The research noted that the considered truss was also subjected to a residual stress, which shifted the beam buckling response. Another example for the usage of latching is reported in Kwon, Hwang, and Lee (2005), describing a microactuator in the form of a truss with a latching effect to serve as a locking mechanism. An example for using the latching phenomena in a thermal actuator is given in Qiu et al. (2005). The authors present a double beam connected to two cantilevers forming two thermal actuators. The thermal actuators shift the double beam from one stable equilibrium to the next by exerting a concentrated force on the beam center. Due to latching, the beam remains at its position, primary or secondary, till a switching forth or back force is applied. Hence, the thermal actuator can act as a switch which distinguishes between two states. In Hansen et al. (2007), a nonvolatile accelerometer which exploits the presence of latching to function without electrical power was presented. In Gerson, Krylov, and Ilic (2010), the possibility of tuning the stability range by means of electrothermal heating is presented. The authors show a technique allowing the control of an actuator and its latching. Similarly, Huang and Yang (2013) presents a method to control the bistability of a curved beam using an applied axial force enhancing both bistability and latching. The approach is used to establish a switch comprised of two beams which push one another back and forth with the usage of an axial force. The presence of latching keeps the beam in its shifted position until an opposite force is applied. A criterion for the latching phenomenon was first derived in Wu, Lin, and Chen (2013) for a double V-beam mechanism exerting a symmetric response only. The validity of the criterion guaranteeing bistability and latching was examined experimentally. In addition, Salinas and Givli (2015) have proposed a new concept of a curved stress free bistable beam for which the secondary equilibrium is more stable than the primary one. The proposed