International Journal of Solids and Structures 51 (2014) 1750–1757

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Bistable buckled beam and force actuation: Experimental validations

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ARTICLE INFO

Article history:
Received 3 October 2013
Received in revised form 11 December 2013
Available online 27 January 2014

Keywords:
Bistable system
Buckling
Experimental validations
Snap-through
Force actuation
Bifurcation

ABSTRACT

This paper presents recent experimental results on the switching of a simply supported buckled beam. Moreover, the present work is focussed on the experimental validation of a switching mechanism of a bistable beam presented in details in Camescasse et al. (2013). An actuating force is applied perpendicularly to the beam axis. Particular attention is paid to the influence of the force position on the beam on the switching scenario. The experimental set-up is described and special care is devoted to the procedure of experimental tests highlighting the main difficulties and how these difficulties have been overcome. Two situations are examined: (i) a beam subject to mid-span actuation and (ii) off-center actuation. The bistable beam responses to the loading are experimentally determined for the buckling force and actuating force as a function of the vertical position of the applied force (displacement control). A series of photos demonstrates the scenarios for both situations and the bifurcation between buckling modes are clearly shown, as well. The influence of the application point of the force on the bifurcation force is experimentally studied which leads to a minimum for the bifurcation actuating force. All the results extracted from experimental tests are compared to those coming from the modeling investigation presented in a previous work (Camescasse et al., 2013) which ascertains the proposed model for a bistable beam.

1. Introduction

A slender elastic beam subject to buckling load is a very simple candidate to design a bistable mechanism. In spite of its apparent basic deformation, such a system possesses relative complexity due to mainly its nonlinearity and instability phenomenon. In a previous work, the authors (Camescasse et al., 2013) reported an analytical study of a bistable system made of a simply supported elastic beam and loaded by a compressive force in its axis direction. The model is based on the elastica theory of beams. The model accounts for large transformations (in particular, a cross-section rotation of large amplitudes) as well as the extensibility property of the beam. In the present work we propose experimental validations of the switching process of the bistable beam under the actuation of localized force.

There has been considerable effort devoted to the design and manufacturing of bistable micro-mechanisms for micro-valves (Goll et al., 1996; Schomburg and Goll, 1998), micro-switches or relays (Matoba et al., 1994; Vangbo and Bäklund, 1998; Jensen et al., 1999; Saif, 2000; Baker and Howell, 2002), fiber-optic switches, digital micro-mirrors (Maekoba et al., 2001) and mechanical memories. More research relies on a bistable buckled beam. This particular class of bistable mechanisms uses deflection to amplify deformation of the elastic beam. The essential advantage of this class of mechanisms remains in stable equilibrium in two distinct positions. This interesting behavior is valuable for micro-mechanical application because power is applied only to have the bistable switched from one stable position to the other one and the state of the system is not lost upon interruption of the power to the system. Magnetically actuated devices are well adapted for actuating bistable mechanisms and used to design MEMS with low energy supply (Gray and Kohl, 2005; Gray et al., 2005). The design of micro- and nano-mechanical devices using bistable beams subject to different kinds of actuation becomes very attractive for systems requiring low level of power consumption and their ability to be miniaturized. Charlot et al. present a micro-mechanical pre-stressed bistable beam of few micro-meters of length to be used as a non-volatile mechanical memory (Charlot et al., 2008). In their work, the actuation of the micro-beam is based on an electrostatic force by applying a voltage to two separate electrodes on each side of the beam. Models for electrically actuated MEMS have been examined by Das and Batra (Das and Batra, 2009). They analyze a perfect electrically conducting

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http://dx.doi.org/10.1016/j.ijsolstr.2014.01.017
0020-7683/

clamped–clamped arch subject to electrostatic force due to a difference of electric potential between a semi-infinite rigid electrode and a deformed beam. Finite element simulations are compared to experimental tests. Park and Hah (Park and Hah, 2008) study analytically and experimentally the actuation of a pre-shaped buckled beam controlled by electromagnetic forces.

Among bistable mechanisms, the pseudo-rigid-body model provides an interesting approach useful for the analysis of compliant systems. This kind of model consists of compliant segments using two or more rigid segments joined by rigid-body joints with springs at the joints to model segment's stiffness (Howell et al., 1996; Edwards et al., 2001; Jensen and Howell, 2004). In the present work, the bistable system is merely a buckled elastic beam which is initially straight. However, it is interesting to report that structures such as shallow elastic arches can be considered in the design of bistable systems. A pioneering experimental study of mode instabilities of elastic arches was conducted by Pippard (Pippard, 1990). Further experimental evidence of instability phenomena of buckled beam or elastic arches were performed by Chen and Su (Chen and Su, 2011). Qiu and co-authors (Qiu et al., 2001) consider a micro-system made of a centrally-clamped parallel bistable beam to showcase the theoretical prediction of the snap-through for central actuation. A study close to the present work has been proposed by Chen and Hung (Chen and Hung, 2011). In their work the authors examine the mid-span actuation and snapping effect of an elastic arch by a localized force. The study focuses on the way of applying the force with respect to the mid-span of the beam. In addition, experimental observations are compared to the theoretical predictions.

In the present study there has been an effort to bridge the modeling phase of a bistable buckled beam (Camescasse et al., 2013) and experimental observations. The emphasis is especially placed on the bifurcation phenomena and the beam response under a localized force. In the next section, we recall the essential ingredients of the theoretical model, the beam geometrical, material parameters, and the loading conditions. In addition, the presentation of the numerical algorithm which has been used to obtain the numerical results of the model is briefly reported. Section 3 is devoted to experimental study. The section first presents, in detail, the experimental set-up. The experimental observations and results are reported for the bifurcation diagram and the bistable response in force–displacement for mid-span and off-center actuations. The experimental results are accompanied by photographs helping us to demonstrate the role played by the buckling modes in the switching process. The final section underlines the most pertinent results and proposes further studies.

2. Description of the system and modeling

We consider a simply supported initially straight elastic beam $[AB]$ of length L_0, width b and thickness h. The fixed Cartesian reference frame $\mathcal{R}_0(A;\vec{e}_1,\vec{e}_2,\vec{e}_3)$ is set such that the x-axis coincides with the neutral axis of the beam, and takes place in the (x,y) plane. The z-axis is then perpendicular to the plane deformation, see Fig. 1.

Under an axial compression P the right end moves towards the left end and the elastic beam buckles. The small-deflection hypothesis is still valid and the distance between the pin-joints becomes $L = L_0 - \Delta L$.

The elastic behavior of the beam is supposed to be linear. The homogeneous beam with Young modulus E, A and I respectively, the cross-sectional area, and the moment of inertia of the cross-section along the z-axis is then actuated to switch from one stable state to the other one by an actuating force $\vec{F} = -F\vec{e}_2$ applied at the point C $(x(s_C) = x_C)$.

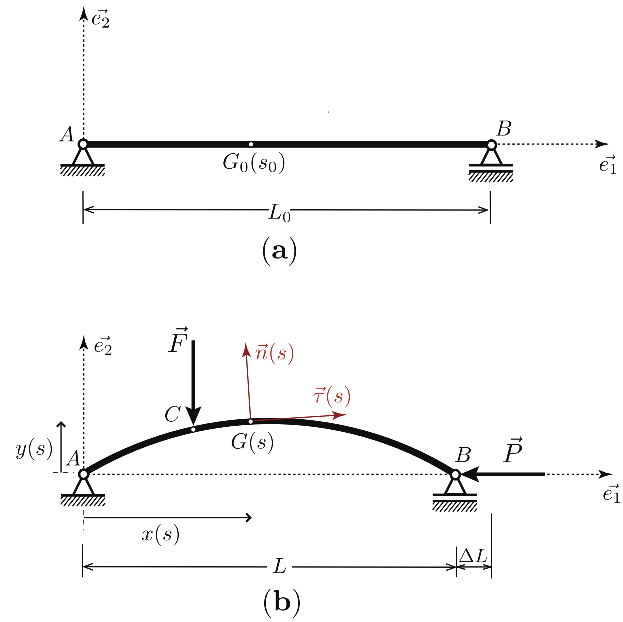

Fig. 1. Simply supported elastic beam: (a) the non loaded beam, (b) the beam in its buckled configuration with the actuating force.

We note by s the curvilinear abscissa along the beam axis in the reference configuration. The unit vector tangential to the current axis of the deformed beam at the point $G(s)$ $\vec{\tau}$ is defined by

$$\vec{\tau}(s) = \frac{d\overrightarrow{AG}}{ds} = x'(s)\ \vec{e}_1 + y'(s)\ \vec{e}_2 = \cos\theta(s)\ \vec{e}_1 + \sin\theta(s)\ \vec{e}_2 \quad (1)$$

where $\theta(s) = (\vec{e}_1, \vec{\tau}(s))$ is the angle of rotation.

On using Eq. (1), the constitutive equations and the beam equations, the static equation for the present buckling beam (valid for both segments $[0, s_C[$ and $]s_C, L_0]$) takes on the form (Camescasse et al., 2013)

$$EI\,\theta''(s) + \delta^{\pm} F\cos\theta(s) + P\sin\theta(s) - \frac{1}{EA}\left[\delta^{\pm}PF\cos(2\theta(s)) - \frac{1}{2}\left(P^2 - (\delta^{\pm})^2F^2\right)\sin(2\theta(s))\right] = 0. \quad (2)$$

$$\text{with} \quad \begin{cases} \delta^- = \delta - 1, & \forall s \in [0, s_C[\\ \delta^+ = \delta, & \forall s \in]s_C, L_0] \end{cases}$$

where the parameter δ denotes the ratio $\delta = \frac{x_C - x_A}{x_B - x_A}$, the relative position of the point C with respect to the support distance.

The nonlinear boundary value problem given by Eq. (2) along with boundary conditions at each end of the beam is solved by using a continuation algorithm based on shooting method combined with a predictor–corrector algorithm to find the shooting parameters (Camescasse et al., 2013).

3. Experimental results and validations

This Section reports a set of results extracted from the experimental tests concerning the bistable beam modeling and the switching process using localized force. The first experimental study deals with the bifurcation diagram which is the basic result for the beam buckling. The following experimental study concerns the force–displacement response of the bistable beam subject to localized force applied perpendicularly to the beam axis. Two situations are examined: (i) an actuating force localized at the mid-span beam and (ii) an off-center actuation. The influence of