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Modeling the nonlinear pull-in behavior of tunable nano-switches

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ABSTRACT

Double-sided nano-devices can potentially be used as tuning switches and variable capacitors. In this paper, the pull-in behavior of double-sided cantilever nano-wires, including the Casimir and partial electrostatic attractions are developed. To increase the tunability, only a piece of substrate plates is electrostatically actuated and conductors' voltage can be different. Herein, the governing nonlinear equation is derived via extended Hamilton's principle. The Galerkin method is used to discretize the differential EOM and the step-by-step linearization method is employed to solve them numerically. The validity of the presented model is confirmed by comparing the theoretical results with the experimental reported ones. The influence of geometrical parameters, i.e. stationary electrodes distance (initial gaps), non-actuated piece length/location as well as wire diameter and length on the instability is investigated. Furthermore, the effect of surface elasticity, residual surface tension and length-scale on the free vibration is examined. It is concluded that the geometric configuration characteristics play significant roles in the pull-in deflection and voltage of nano-structures, which should be considered in applying design and tuning applications.

1. Introduction

Micro- and Nano-electromechanical systems (MEMS and NEMS) are used in several applications, such as switches, actuators, sensors, narrow band filtering atomic force microscopes as well as mass and force detection (Abbasi & Abbasi, 2015, Azizi, Ghazavi, Khadem, Rezazadeh, & Cetinkaya, 2013, Azizi, Ghazavi, Rezazadeh, Ahmadian, & Cetinkaya, 2014, Korayem, Karimi & Sadeghzadeh, 2014, Maani Miandoab, Pishkenari, Yousefi-Koma, & Tajaddodianfar, 2014, Shaat & Abdelkefi, 2015). Several important building blocks in NEMS consist of at least two conductive electrodes in which one of them is movable. The deformable electrode deflects toward the fixed substrate one due to the electrostatic Coulomb force and when this attraction becomes larger than the corresponding restoring one, leading to the unstable collapsing (pull-in instability). Investigating this phenomenon in NEMS has attracted industrial and research attentions. While the pull-in voltage confines the stable range of systems, determining the critical deflection and voltage, are essential in the design procedure of various micro- and nano-structures (Azizi, Ghazavi, Khadem, Yang, & Rezazadeh, 2012, Baghani, 2012, Dehrouyeh-Semnani, Mostafaei, & Nikkhah-Bahrami, 2016, Farokhi & Ghayesh, 2016, Rahaeifard & Ahmadian, 2015, Shafiei, Kazemi, Safi, & Ghadiri, 2016, Shojaeefard, Khalkhali, Khakshournia, & Malmir, 2014, Zeighampour & Beni, 2014).

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Nano-devices with different geometric configurations may suffer from large deformation. Furthermore, these structures can experience different sources of non-linearity, such as geometric non-linearity as well as electrostatic excitation and dispersion (Casimir and van der Waals) forces. As a result, the behavior of nano-scale structures is fundamentally nonlinear. For similar nano-devices with differential equations, except a few approximate analytical solutions, it was not reported exact closed-form solution, yet. Anderson, Nayfeh, and Balachandran (1996) experimentally demonstrated that the ignored nonlinear curvature is significant in the response of beams. The impact of geometric non-linearity on the beam structure was analyzed by Chaterjee and Pohit (2009). Moreover, in Refs. Dai and Wang (2015), Mobki, Sadeghi, Rezazadeh, and Fathalilou (2014), Wang and Wang (2014), the difference between linear and nonlinear results was shown that the geometrical nonlinear deformation makes a great influence on the pull-in behavior. The results of this review exposed that the non-linearity has considerable effect on the pull-in instability of electromechanical systems and neglecting this effect leads to incorrect results.

The appearance of new influences through the scale alternation in geometry can cause several additional terms into the theory of nano-scale structures that are ignored in the other structures. For example, the dispersion attractions can play an important role in the pull-in phenomenon, according to the gap between the electrodes (Ganguly & Desiraju, 2008, Lamoreaux, 2005, Mokhtari, Farrokhabadi, Rach, & Abadyan, 2015, Pourkiaee, Khadem & Shahgholi, 2015). These forces are extensive in the nano-scale, while their impacts on other scales are not noteworthy (Ma, Jiang, & Asokanthan, 2010). In Refs. Farrokhabadi, Abadian, Kanjouri, and Abadyan (2014), Farrokhabadi, Abadian, Rach, and Abadyan (2014), the effects of dispersion forces on the instability revealed that neglecting them in the nano-scale can cause incorrect analysis and the predicted pull-in voltage will be overestimated. It must be noted that for large primary separation, the quantum vacuum fluctuation (Casimir) should be considered instead of intermolecular (van der Waals) force (Ramezani, Alasty, & Akbari, 2007).

Another significant effect, which can affect the response of materials and become more dominant in nano-structures, is the surface energy. Surface effects are divided into surface elasticity as well as residual tension effects. Because of the essentially large ratio of surface area to volume of nano-devices, surface energy can make a considerable contribution to the structural behavior (Ansari, Ashrafi, Hosseinzadeh, & Firouznia, 2014, Ghorbanpour-Arani, 2015, Jam & Samaei, 2013, Kurhekar & Apte, 2013, Kurhekar & Apte, 2012, Mohammadimehr, Rousta Navi, & Ghorbanpour Arani, 2014). Recently, the pull-in instability of nano-actuators/sensors considering the residual surface stress as well as surface elasticity effects has been investigated. Wang and Wang studied the impact of surface energy on the pull-in instability of cantilever (Wang, Kitamura, & Wang, 2015) and double clamped (Wang & Wang, 2014) nano-beams. Moreover, the surface energy of NEMS cantilevers and tweezers were investigated by Dai and Wang (2015) and Mohebshahedin and Farrokhabadi (2015), respectively. The results illustrate that the surface effects made an important contribution to the pull-in instability of nano-devices.

Beside the non-linearity, dispersion forces and surface energy, the size effect of material properties at small scale is another essential issue that should be considered in nano and micro systems modeling. Experiments demonstrate a hardening behavior in the elastic resistance of the conductive metals, as the dimensions become comparable to the internal material length-scale (Lam, Yang, Chong, Wang, & Tong, 2003, McFarland & Colton, 2005). The classical continuum theory cannot able to model the size dependency of materials and structures at small scales. According to this, the more general non-classical theories, including strain gradient theory (Lam et al., 2003), couple stress theory (CST) (Ejike, 1969), non-local elasticity (Eringen & Edelen, 1972), modified couple stress theory (MCST) (Yang, Chong, Lam, & Tong, 2002), etc. have been extended to consider the size-dependent behavior. In more recent researches, the stability of NEMS considering the size effect has been studied intensely (Dehrouyeh-Semnani & Bahrami, 2016, Ghayesh, Farokhi, & Alici, 2016, Hosseini & Bahaadini, 2016, Rahmani & Pedram, 2014, Shaat & Abdelkefi, 2016). The results indicate the importance of this effect on the response and structural behavior of electromechanical systems.

It is worth to mention that, the structural architecture is another significant point in the mechanical systems. There are several types of micro- and nano-constructions, such as multi-terminal architectures (Axelsson et al., 2005, Loh et al., 2012) and some more complex constructions (Do, Lishchynska, Delaney, & Hill, 2012, Koduru, Obili, & Cecilia, 2013, Wang & Wang, 2015). Furthermore, double-sided plans are provided for different purposes, in which the movable beam is suspended between two conductive stationary electrodes (Abadian et al., 2016, Ghalambaz, Ghalambaz, & Edalatifar, 2016, Mobki, Rashvand, Afrang, Sadegh, & Rezazadeh, 2014, Sedighi, Koochi, Daneshmand, & Abadyan, 2015). General models, which could account various varieties of structures, should be developed to consider the structural configuration for NEMS. Herein, a nano-device fabricated from a cantilever wire between two actuated piecewise fixed electrodes is considered. As a result, in this double-sided switch, the electrostatically actuated length of each conductor is shorter than movable electrode. To evaluate the operating condition of such NEMS/MEMS constructions, since the geometric configuration of the substrate significantly affects the pull-in behavior, it must be considered in applying design and tuning applications. Therefore, double-sided actuated piecewise nano-devices such as tunable switches, capacitors, actuators, sensors, resonators, detectors, oscillators and filters are extensively designed, analyzed, fabricated and operated.

In the literature review, the Casimir force, non-linearity, surface energy, size dependency as well as geometrical configuration, were distinctly taken into account. All of these parameters play significant role in the nano-structures and it is important to consider them simultaneously. In the present study, the authors illustrate the impact of the mentioned parameters on the pull-in behavior and response frequency of nano-devices under electrostatic force. It is worth noting that, the combined effect of all above characteristics on the nonlinear instability of nano-wires, has not been considered so far. To this aim, Hamilton's principle is applied to obtain the governing equation. To solve governing differential equation, a