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Modified continuum model for stability analysis of asymmetric FGM double-sided NEMS: Corrections due to finite conductivity, surface energy and nonlocal effect

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ABSTRACT

Finite conductivity, surface energy and nonlocal effect can influence the electromechanical performance of micro/nano-electromechanical systems (MEMS/NEMS). However, these factors are yet ignored on stability analysis of MEMS/NEMS fabricated from functionally graded materials (FGM). In this paper, dynamic stability of double-sided NEMS fabricated from non-symmetric FGM is investigated incorporating finite conductivity, surface energy and nonlocal effect. The Gurtin–Murdoch model and Eringen's elasticity are employed to consider the surface energy and nonlocal effect, respectively. Effect of finite conductivity of FGM on electrostatic and Casimir attractions is incorporated via relative permittivity and plasma frequency of the material. The stability analysis of the nanostructure is conducted by plotting time history and phase portraits. Moreover, bifurcation analysis is conducted to investigate the stability of the fixed points of the nano-structure. The validity of the proposed model is examined by comparing the results of the present study with those reported in the literature. The impact of various parameters i.e. finite conductivity, nonlocal parameter, surface stresses and material characteristics on the dynamic instability of the NEMS are addressed.

1. Introduction

With recent developments in nano-scale manufacturing technologies, functionally graded materials (FGMs) are being considered as potential structural materials with promising applications in optoelectronics, biomechanics, tribology and micro/nanotechnology [1,2]. Functionally Graded Materials belong to a class of advanced materials with continuously varying properties over the thickness. The graded properties of FGMs result in high resistance to temperature gradients and significant reduction in the stress concentrations, thermal stresses and residual stresses. Due to the inherent properties of FGMs as the multi-functional materials, these advanced composites are very good candidates for smart structures. Interestingly, FGMs have received considerable attention in developing ultra-small systems and miniature devices. Previous researchers have theoretically addressed the mechanical behavior of FGM miniature elements. Eltaher et al. [3] studied the static bending and buckling of functionally graded nanobeams. They indicated that, the material-distribution profile may be manipulated to change the maximum deflection and maximize the critical buckling load. Ke and Wang [4] investigated dynamic stability of FGM micro-beams using the modified couple stress theory. Nonlinear finite element model of functionally graded microbeams by considering the power-law variation of material through the beam height, and microstructure length scale parameter was developed by Arbind and Reddy [5] for the Euler–Bernoulli and the Timoshenko beam theories. They demonstrated that the effect of micro-structural parameter is to stiffen the micro-beams. The vibration of axially functionally graded material (AFGM) nanobeam was investigated by Zeighampour and Tadi Beni [6] by employing strain gradient theory. They studied the impacts of the diameter of the nanobeam, the stiffness and damping of the visco-Pasternak foundation on the natural frequency of the nanobeams. With recent growth in micro/nanofabrication technology, FGMs are explored for constructing micro/

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nano-electromechanical systems (MEMS/NEMS) [7–9]. In this regard, some researchers have focused on modeling FGM-fabricated MEMS/NEMS. Abbasnejad et al. [10] studied the mechanical behavior of a fixed–fixed FGM micro-beam subjected to a nonlinear electrostatic pressure using modified couple stress theory and classic theory. They showed that by increasing the power law constant, the position of the saddle node bifurcation moves to the right in the state-space. Ji et al. [11] investigated the pull-in instability and free vibration of functionally graded poly-SiGe micro-beams under combined electrostatic force and axial residual stress, with an emphasis on the effects of ground electrode shape. The dynamic pull-in behavior of FGM nano-actuators has been previously addressed by the authors [12] using classical continuum elasticity. In present article, a modified continuum model is proposed to investigate the pull-in instability of double-sided beam-type NEMS bridges made of asymmetric FGM beam. Three important modifications are considered in order to increase the accuracy of the model.

The first modification is incorporating the finite conductivity of FGMs in the equation of motion of the nano-bridge. It is well established that for precise simulation of NEMS, both Casimir and Coulomb forces should be considered in deriving the governing equation [13]. The strength of Casimir and Coulomb forces between interacting surfaces strongly depends on the material characteristics of the surfaces [14,15]. Correction of Casimir force due to finite conductivity of the interacting flat plates have been calculated to first order by Hargraves [16] and to second order by Bezerra et al. [17]. These researchers have proposed simple approximations for Casimir force as a function of plasma wavelength of material. Similar to Casimir force, the Coulomb attraction between two FGM plates (with finite conductivity) is less than that of perfect metals. The corrected Coulomb force for FGM NEMS can be obtained considering the dielectric characteristics (permittivity) of FGM. It should be mentioned that all the previous researchers who investigated FGM NEMS have used force relations that are valid only for perfectly conductive metals. However, this is not acceptable for graded materials especially ceramic-metal FGMs. Herein, the finite conductivity of FGM is taken into account for computing Coulomb attraction between surfaces as well as Casimir force.

The second correction is due to the presence of surface layer that affects the elastic stiffness of the micro-/nano-beams. The experimental results have demonstrated that for nanoscale structures, the surface effects become significant due to the high surface/volume ratio [18]. Gurtin and Murdoch [19] developed a surface elasticity theory for isotropic materials that model the surface layer of a solid as a membrane with negligible thickness. A size-dependent finite element model, for Mindlin plate theory accounting for the position of the neutral plane for continuum incorporating surface energy effect, was proposed by Shaat et al. [20] to study the bending behavior of ultra-thin FGM plates. Wang et al. [21] summarized the advances in the surface stress effect in mechanics of nano-structured elements, including nanowires, nanobeams, and nano-films. Sedighi [22] investigated the dynamic pull-in instability of nonlocal nano-bridges incorporating the surface effect and inter-molecular forces. The influence of surface effects on the pull-in instability of a cantilever nano-actuators was investigated by Koochi et al. [23] incorporating the effect of Casimir attraction. Ansari et al. [24] examined the instability characteristics of hydrostatically and electrostatically actuated circular nanoplates including surface stress effect on the basis of Gurtin–Murdoch elasticity theory. Hosseini-Hashemi and Nazemnezhad [25] studied the nonlinear free vibration of simply supported FG nanoscale beams with considering surface effects. They discussed the influences of the FG nanobeam length, volume fraction index, amplitude ratio, mode number and thickness ratio on the normalized nonlinear natural frequencies of the FG nanobeams. In the current study, the impact of surface layer on the pull-in behavior of FGM nano-bridges is taken into account.

The third modification that is considered in the proposed model is the nonlocal effects that appears at micro/nanoscales. In order to modeling the nonlocal effects, size-dependent continuum theory such as Eringen elasticity has been proposed for modeling the size phenomenon in nanostructures [26]. This theory has been employed to investigate the size dependent behavior of miniature structures. Li et al. [27] presented the analytical solution for the transverse vibration of nano-beams subjected to initial axial force based on the nonlocal theory. To simulate transient thermo-elastic responses of the nanostructure subjected to a sudden thermal loading, Yu et al. [28] extended the classical thermo-elastic models using Eringen's nonlocal elasticity and Caputo fractional derivative and memory dependent derivative (MDD). Reddy and El-Borgi [29] derived the governing equations of Timoshenko beams assuming the Eringen's nonlocal differential model and modified von Kármán nonlinear strains. They also developed the finite element models of the resulting equations and presented the numerical results for various boundary conditions, showing the effect of the nonlocal parameter on the deflections. Kiani [30] studied the axial buckling behavior of vertically aligned single-walled carbon nanotubes based on the nonlocal continuum theory and addressed the roles of the influential factors on both in-plane and out-of-plane axial buckling loads. Jung et al. [31] employed the modified couple stress theory which accounts for the asymmetric couple stress tensor, for buckling analysis of S-FGM nanoplates embedded in Pasternak elastic medium. They addressed the effects of power law index, small scale coefficient, aspect ratio, side-to-thickness ratio, loading types, and elastic medium parameter on the buckling load of S-FGM nanoplates. Ebrahimi and Salari [32] employed the nonlocal Euler–Bernoulli beam theory for vibration analysis of functionally graded (FG) size-dependent nanobeams by using Navier-based analytical method and investigated the effects of systems parameters on the normalized natural frequencies of the FG nanobeams. In another research [33] they studied the thermal effect on free vibration characteristics of functionally graded (FG) size-dependent nanobeams subjected to an in-plane thermal loading using the same method of solution. The nonlocal elasticity has also been applied for simulating the pull-in instability of MESM/NEMS actuators fabricated from isotropic material. In this research work, the Eringen elasticity is employed for considering the influence of nonlocal effects on the pull-in characteristics of the double-sided nano-bridge.

The present article is organized to study the effects of finite conductivity of FGMs on the dynamic instability of double-sided NEMS bridge considering the surface energy and nonlocal effects. To this end, the influences of actuation voltages, nonlocal parameter, properties of FGM materials, surface stresses and Casimir force on the pull-in parameters are investigated. To verify the soundness of the present analysis, the obtained results are compared with the reported results in the literature.

2. Mathematical modeling

Fig. 1 depicts an asymmetric functionally graded nano-bridge actuated by a pair of parallel-plate electrodes with length l, thickness h, width b and initial gaps g_1 and g_2 from the bottom and top substrates which is under DC actuation voltages V_1 and V_2, respectively. The distance of any point of the nano-beam from the neutral axis and the top surface are represented by z and $\tilde{z}$, respectively. Moreover, the distance of the neutral axis from the top surface is denoted by $\tilde{z}_c$. The coordinate system is also illustrated in Fig. 1.