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Dynamic instability analysis of electrostatic functionally graded doubly-clamped nano-actuators

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ABSTRACT

This paper is dedicated to investigate the dynamic instability of functionally graded nano-bridges considering Casimir attraction and electric filed actuation. The nano-bridge is initially at rest and actuated by suddenly DC voltage. The fundamental frequency of the system is obtained asymptotically by employing modern approach namely Parameter Expansion Method (PEM). The effects of actuation voltage, properties of FGM materials and intermolecular force on the dynamic pull-in behavior are studied. It is exhibited that in order to achieve the acceptable approximations for fundamental frequency as well as the analytic solution, six terms in series expansions should be taken into account. Comparison between the obtained results based on the asymptotic analysis and the reported results in the literature, verify the strength of the analytical procedure. Finally, the influences of applied voltage and gradient power of functionally graded materials on the dynamic pull-in voltage and pull-in time of vibrating nano-actuators are explained.

1. Introduction

Functionally Graded Material (FGM) is an advanced composite which characterized by gradual variation in properties over its volume. It is an anisotropic composite material in which material gradient is constructed over two different materials and material properties change continuously from one surface to the other and thus eliminates the stress concentration found in laminated composites [1]. FGMs are generally made of a mixture of ceramic and metal to satisfy the demand of ultra-high-temperature environment and to eliminate the interface problems, as ceramic has a low thermal conductivity and thus excellent temperature residence. Recently, many researchers have been focused on studying the static and dynamic behavior of FGM structures [2–8]. FGMs find increasing applications in micro- and nano-structures, such as thin films in the form of shape memory alloys [4,5] and micro- or nano-electro-mechanical systems (MEMS/NEMS) [6–8].

Hasanyan et al. [2] investigated the instabilities in micro-thermo-electro-mechanical FG plates due to the heat produced by the electric current (Joule heating). The dependence of the electric conductivity upon the temperature and the gradation of material properties were considered in modeling the instability of the FG plates. They showed that the instability voltage strongly depends upon the variation through the thickness of the volume fractions of the two constituents. Moreover, it was found that the thermo-electromechanical response of the system might be stable or unstable depending upon the initial conditions and values of material parameters. Simsek and Yurtcu [9] examined the static bending and buckling of a functionally graded (FG) nanobeam based on the nonlocal Timoshenko and Euler–Bernoulli beam theory and discussed the effects of nonlocal parameter, aspect ratio, various material compositions on the static and stability responses of the FG nanobeam. A mathematical model was proposed by Kiani [10] to explore the vibrations and instabilities of moving functionally graded (FG) nanobeams. He studied the effects of the power-law index, small-scale parameter, length of the FG nanobeam, and its velocity on the frequencies and stability of the moving nanostructure and discussed the divergence and flutter instabilities of moving FG nanobeams. Ke and Wang [11] investigated the

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dynamic stability of microbeams made of functionally graded materials (FGMs) based on the modified couple stress theory and Timoshenko beam theory. They also discussed the influences of the length scale parameter, gradient index and length-to-thickness ratio on the dynamic stability characteristics of FGM microbeams with hinged–hinged and clamped–clamped end supports. Nabian et al. [12] studied the stability of a functionally graded clamped–clamped microplate subjected to hydrostatic and electrostatic pressures. They investigated the effects of the electrostatic and hydrostatic pressure changes on the deflection and stability of the micro-plate. Ansari et al. [13] investigated the free vibration analysis of size-dependent functionally graded microbeams based on the strain gradient Timoshenko beam theory. They also explored the effects of the length scale parameter, gradient index and slenderness ratio on the vibrational behavior of FGM microbeams. Akgöz and Civalek [14] studied the longitudinal free vibration analysis of axially functionally graded microbars based on the strain gradient elasticity theory and showed the influences of additional material length scale parameters, material ratio, slenderness ratio and ratio of Young's modulus on natural frequencies of axially functionally graded microbars.

In the case of ultra-small structures, new phenomena such as Casimir forces [15] which represent the attraction between two metallic plates arising from the quantum fluctuations [16] should be considered. Pull-in behaviors of nano-structures have been investigated by many researchers using different theorems and hypotheses [17–19]. Rafiei et al. [20] studied the size-dependent vibration behavior of single-walled carbon nanotubes conveying fluid by employing nonlocal elasticity theory. Koochi et al. [21] investigated the instability of nano-actuators considering the dispersion force and surface stress effects. Eltaher et al. [22] developed a finite element model based on the nonlocal elasticity and examined the vibration behavior of nano-scale beams by considering the surface effect.

Many asymptotic approaches have been introduced so far to approximate the solution of static and dynamic behavior of nonlinear systems such as He's Max–Min Approach (MMA) [23], Homotopy analysis Method [24], Variational Iteration Method-II [25], Variational Approach [26], Homotopy Perturbation Method (HPM) [27], Adomian decomposition [28], Variational Iteration Method [29], Hamiltonian Approach [30], Homotopy Perturbation Method with an auxiliary term [31,32] and Parameter Expansion Method (PEM) [33].

The present article is organized to explain the dynamic pull-in behavior of FGM nano-actuators. The fundamental frequency and analytic solution of vibrating nano-bridges in the presence of Casimir intermolecular force is obtained using PEM. To obtain high accurate approximate solutions, six terms in series expansions is taken into consideration. The influences of actuation voltage, dispersion force and material properties on the instability of nano-actuators are studied. Finally, the impact of applied voltage and gradient power of functionally graded materials on the dynamic pull-in voltage and pull-in time of nano-actuators is also discussed.

2. Mathematical modeling

Consider a nano-bridge made of functionally graded material above a rigid plate as illustrated in Fig. 1. The beam has length l, thickness h, width b and initial gap g which is actuated by step DC voltage V. 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 $\tilde{z}_c$ and the configuration of coordinate system is also shown in Fig. 2. It is assumed that the FGM nano-beam property which is made of metal and ceramic phases, along its thickness can be expressed by the following relations:

$$E(\tilde{z}) = E_c + \left(\frac{\tilde{z}}{h}\right)^n (E_m - E_c) \tag{1}$$

$$\rho(\tilde{z}) = \rho_c + \left(\frac{\tilde{z}}{h}\right)^n (\rho_m - \rho_c) \tag{2}$$

The governing equation of motion for vibrating nano-actuator assuming Euler–Bernoulli beam theory in the presence of applied voltage and Casimir effect can be written as follows:

$$m_0 w_{tt} + (EI)_{eq} w_{xxxx} - \left(N_0 + \frac{(EA)_{eq}}{2l}\int_0^l \left(\frac{\partial w}{\partial x}\right)^2 dx\right)\frac{\partial^2 w}{\partial x^2} - F_{es} - F_C = 0 \tag{3}$$

In the aforementioned equation, the equivalent flexural rigidity $(EI)_{eq}$, axial rigidity $(EA)_{eq}$ and mass per unit length m_0 and of FGM nano-structure can be expressed as:

$$(EI)_{eq} = \int_0^h (\tilde{z} - \tilde{z}_c)^2 \left[E_c + \left(\frac{\tilde{z}}{h}\right)^n (E_m - E_c)\right] b d\tilde{z} = bh^3 E_c \tilde{\mu}(n) \tag{4}$$

$$(EA)_{eq} = \int_0^h \left[E_c + \left(\frac{\tilde{z}}{h}\right)^n (E_m - E_c)\right] b d\tilde{z} = bhE_c\tilde{E}(n) \tag{5}$$

$$m_0 = \int_0^h \left[\rho_c + \left(\frac{\tilde{z}}{h}\right)^n (\rho_m - \rho_c)\right] b d\tilde{z} = bh\rho_c\tilde{\rho}(n) \tag{6}$$

in which

$$\tilde{\mu}(n) = \frac{12\mu_{mc}^2 + (4n^3 + 16n^2 + 28n)\mu_{mc} + n^4 + 4n^3 + 7n^2}{(n + \mu_{mc})(n+3)(n+2)^2} \tag{7}$$

$$\tilde{E}(n) = 1 + \frac{(\mu_{mc} - 1)}{n+1} \tag{8}$$

$$\tilde{\rho}(n) = 1 + \frac{(\rho_{mc} - 1)}{n+1} \tag{9}$$

In Eqs. (7)–(9), the parameters μ_{mc} and ρ_{mc} represent the elastic modulus and density ratio of metal to ceramic phases of nano-beam. In addition, in the governing Eq. (3), the symbols F_{es} and F_C denote the electrostatic and Casimir forces, respectively. In order to explain the electrostatic actuation force, the "fringing-field"

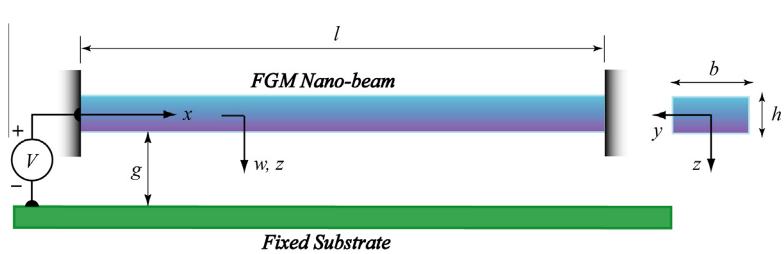

Fig. 1. Configuration of an actuated FGM nano-bridge.