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Optimal design and system characterization of graphene sheets in a micro/nano actuator

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ABSTRACT

In this article, an element free Galerkin method (EFGM) is used for dynamic characterization of a capacitive nanoactuator as subjected to a DC voltage by using a proposed nonlocal plate theory. The system governing equations of an electrostatic nanoactuator are first derived based upon the theory of nonlocal Kirchhoff plate. The intermolecular forces, such as Casimir and van der Waals forces, are included in the proposed model. The weak form representation of equilibrium equations is presented based on Hamilton principle and a discrete moving least squares (MLS) approximation for the shape function. Since the MLS approximation does not satisfy the principle of Kronecker delta, a penalty method is then imposed upon to equip as auxiliary boundary conditions. The discrete weak form is adopted to solve for eigenvalue solutions and natural frequencies of the plate. Since numerical experimental results indicate that the number of nodes that scattered in the working domain can affect final solutions dramatically, a calibration scheme is introduced into the proposed modeling system beforehand by using some referred known functions. Eventually, the characterization dynamic behaviors for a nanoactuator with designated DC voltage is made possible. The results indicate that the proposed modeling approach and computational program are accurate and feasible for design and system characterization of single-layered graphene sheets (SLGS) by the adjustment of scale effect to allow the associated pull-in voltage of the device to be optimally designated.

1. Introduction

MEMS and NEMS are rapidly developed in recent years along with the advancement of microelectronic component compatibility and integration of manufacturing techniques. Micro/nano plates, such as graphenes, are of basic elements frequently used in different industrial sectors, including microactuators, microswitches, biosensors, nanowires, nanoprobes, ultra-thin films and MEMS/NEMS for better electrical, mechanical and thermal signatures. Because of that, the studies on the dynamic behaviors of these key elements have received quite considerable attention in the past decade by researchers. Arash and Wang [1] showed that the small length scale effect should be taken into consideration in the modeling of micro/nano structures since material properties at the nanoscale are of size-dependent.

Physical experiments and molecular dynamic simulations are all of appropriate methods for accurate mechanical modeling of micro/nano structures. However, controlled experiments for systems of nano scale are difficult. On the other hand, molecular dynamic simulations are computationally expensive. Hence, models of modified continuum models that can capture small scale effects have been introduced for the characterization of mechanical system behaviors of these tiny structures in recent years. Among continuum models that are capable of capturing small scale effects of the system, nonlocal elasticity theory [2] is the one that received more attention lately.

Among various micro-electromechanical systems (MEMS) applications, the micro-actuator is the distinct one. The drive for the system can be divided into electrostatic, thermal, magnetic, piezoelectric and hydraulic types. Among these, the electrostatic drive has many advantages, such as a fast response and low power loss. Therefore, it is more widely used than any other actuators available in the market. As far as the electrostatic drive micro-actuator is concerned, the adsorption voltage, namely, pull-in voltage, is a substantial design parameter. By using the drive voltage to control the position of two parallel electrode plates of the actuator, the upper and lower electrode plates will be able to touch together momentarily at pull-in voltage. This particular dynamic behavior is called adsorption phenomena, and can be occasionally observed in

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electrostatic drive RF switch, in which the operating voltage is closely dependent on the adsorption voltage. Because the electrostatic force is too small to influence large elements, it is often ignored. However, in micro-electromechanical systems (MEMS), electrostatic force has become such as great drive, so that the development of micro-electromechanical systems (MEMS) become feasible and gradually emerged as a good investment in research to explore the system capabilities.

Various meshfree methods have in recent years been developed for structural analysis of plates and shells. A meshfree method is a method that is used to establish a system of algebraic governing equations without using a predefined mesh for domain discretization [3]. All meshfree methods use a set of nodes scattered in problem domain without any element connectivity among them. Element free Galerkin method (EFGM) is one of well-known meshfree methods using moving least square (MLS) as approximation function. Since MLS approximation functions do not satisfy the principle of Kronecker's delta, enforcement of the essential boundary conditions requires various special techniques, including direct collocation, Lagrange multipliers, penalty method, etc. Although various versions of meshfree methods have been applied for structural analysis, few researchers have applied a systematic EFGM to solve the bending and free vibration problems of plates and shells as far.

In the present study, vibrational behavior of single-layer graphene sheets is studied. Small scale effect is introduced into the model using nonlocal elasticity theory. Equilibrium system equation of the plate is obtained based on the theory of Kirchhoff plate. Weak form of equilibrium system equation is obtained. Natural boundary conditions are imposed automatically for weak form solutions. Essential boundary conditions are then enforced by using the penalty method. Both eigenvalue problem method and dynamic response method are employed to characterize structural dynamic behaviors. Vibration frequencies of the sheet are obtained and then compared with those obtained by using local plate theory. Results of comparative studies of the effect of applied voltage and associated nonlocal parameter on the variation of vibration frequencies are discussed. The threshold of applied voltages and the design of low-voltage micro-switches using critical dynamic pull-in are presented and concluded [4].

2. Basic governing equations

2.1. Fundamentals for the design of an electrostatic drive micro-actuator

Electrostatic drive micro-actuator can be categorized into different types including parallel plate capacitive model, comb drive model, and the scratch drive model. Since plates are widely used in various industrial and daily environment, and their application to electrostatic drive micro-actuators possesses advantages of structural simplicity, power consumption economics and fast response, it has drawn many attention of scientists and researchers to design and characterize for various shapes of plates. Among these applications, the device of parallel plate capacitor electrostatic actuator is one of the popular ones. In view of the application potential, this paper is intended to characterize the dynamic behaviors of the electrostatic actuation microplate actuator for optional pull-in voltage design and system signature.

For an electrostatic drive micro-actuator, the two plate electrodes can produce electrostatic force in between as drive voltage is applied. The electrostatic force will cause the deformation of the structure as the distance between two electrodes is moved closer to each other. As the space between the two electrodes becomes smaller, the static electricity increases, and the pull-in behavior becomes a nonlinear coupling problem.

Generally speaking, the deformation of a plate can be small deformation, large deformation or medium deformation. For an actuator made of fine finishing sheets, it can be considered as the thin plate of small deformation induced by bending moments. This article is designated to investigate the dynamic behaviors of microplates in micro-actuators with a small deformation induced by thin plate bending.

A parallel plate capacitor is composed of two parallel plate conductors for the storage of electrical charges. It is separated by the dielectric materials in the middle of the two plates, as shown in Fig. 1. When a voltage V is applied in between the parallel electrode plates and then can produce a capacitance of value C, that can is given as

$$C = \frac{Q}{V} \tag{1}$$

where Q is the amount of charges being stored. According to Gauss theory, field strength E_0 of the two electrode plates is related the amount of charges, being stored and can be expressed as

$$E_0 = \frac{Q}{\bar{\varepsilon} A} \tag{2}$$

where $\bar{\varepsilon}$ is the permittivity which is equal to $\bar{\varepsilon} = \varepsilon_0 \varepsilon_r$, and ε_r is the relative dielectric constant between two electrode plates, ε_0 is permittivity in vacuum.

Since the voltage V is equal to the product of the strength of E_0 and gap d of the field, the capacitance value C of the parallel capacitor can be given as

$$C = \frac{\bar{\varepsilon} A}{d} \tag{3}$$

The electrical energy U_e stored in the parallel capacitors can be expressed as

$$U_e = \frac{1}{2} C V^2 \tag{4}$$

The electrostatic force F_d of the parallel capacitors are equal to the gradient of the stored energy U_e, and can be expressed as

$$F_d = \left| \frac{\partial U_e}{\partial d} \right| = \frac{\bar{\varepsilon} A V^2}{2 d^2} \tag{5}$$

Eq. (5) indicates that the magnitude of the electrostatic force decreases rapidly as the distance d of the bipolar plates increases. Since the electrostatic force belongs to a short-range force, it is required for us to explore the pitch in micro/nano scale that becomes most effective. By assuming that the electric field between two electrode plates is uniform, and relative dielectric constant is of 1 ($\varepsilon_r = 1$, so $\bar{\varepsilon} = \varepsilon_0$), the potential energy that is stored in between the two electrode plates can then be given as

$$U_e = \frac{\varepsilon_0 V^2}{2} \iint_\Omega \frac{1}{(d - w)} dxdy \tag{6}$$

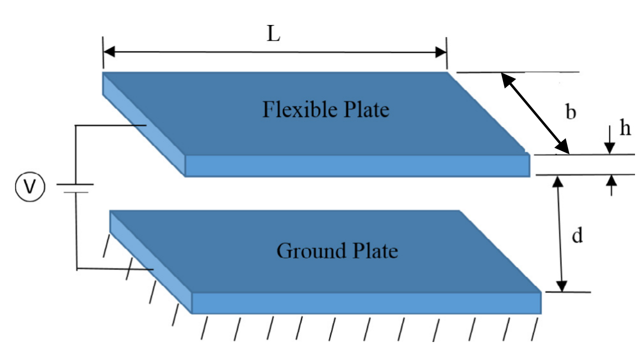

Fig. 1. Schernatic diagram of two microplates driven by DC voltage.