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Nonlinear dynamic characteristics of graphene/piezoelectric laminated films in sensing moving loads

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ABSTRACT

This paper reports the result to investigate into the nonlinear dynamic response characteristics of GP (graphene/piezoelectric) laminated films in sensing moving transversal load induced by externally moving adhesive particles or molecules, based on the nonlocal elasticity theory and Von Kármán nonlinear geometric relations. A reformulated differential quadrature method (DQM) is proposed to solve the nonlinear dynamic equations constructed with the Hamilton's principles and Galerkin method. Several examples are presented to validate the accuracy and convergence of present methods. The effects of some key factors, such as the magnitude and velocity of moving load, the number of loads, the external linear voltage, the scale-dependent nonlocal parameter and the thickness of piezoelectric layer on the nonlinear dynamic response characteristics of GP (graphene/piezoelectric) laminated films are discussed. Results show that the geometrical nonlinearity should be paid much attention in analyzing relative large deflection problems of laminated films. Moreover, both the external voltage and moving velocity play significant roles in the nonlinear dynamic responses of GP-based nano-sensor in sensing a moving load. The meaningful results can serve as references for the design of a nano-sensor or other GP-based electromechanical devices.

1. Introduction

Over the past decade, graphene has attracted tremendous attentions in experimental and theoretical studies owing to its excellent mechanical, electrical, optical and thermal properties [1–7], and continually promotes the investigations on its further properties, applications and derivatives. Since graphene was firstly exfoliated by Novoselov group [8], graphene shows great potentials in the design of nanoelectromechanical systems (NEMS), which can be used in various engineering aspects, such as health monitoring, food or medicine detection, environmental monitoring, biomedical applications, chemical process, etc [9–12]. It is well known that pristine graphene is non-piezoelectric material due to its intrinsically centrosymmetric crystal structure, which limits its applications to various advanced nanoscale electronics and optoelectronics. However, several theoretical and experimental works have announced the possibilities of piezoelectricity in graphene by introducing specific in-plane defects [13], the selective surface adsorption of atoms [14,15], or introducing engineered strain [16,17], etc. In view of above studies, the graphene/piezoelectric (GP) laminated films composed of graphene sheet and piezoelectric material is proposed in this paper, which couples the excellent material properties of graphene and piezoelectric materials and could be treated as a candidate material of nano-sensors or energy harvester [18].

Actually the laminates composted of graphene and piezoelectric materials (ZnO, PVDF, PZT, LiNbO3, etc) have been successfully synthesized due to some emerging technologies. For example, a kind of loud speaker with a layer polyvinylidene fluoride (PVDF) and two layers graphene were fabricated by Shin et al. [19] and Xu et al. [20], and showed some extraordinary characteristics like flexible, transparent, magnet-free and any designed shape or size. Using pulsed laser deposited technology, Zeng et al. [21] studied the mechanism of ZnO/graphene films, which presented excellent optical properties. In another work, Battista et al. [22] improved the absorption ability of solar radiation by coating LiNbO3 on graphene in a solar energy harvesting system. Recently, Rahman et al. [23] fabricated flexible energy harvesters using PVDF-graphene nanocomposites, which showed remarkable dielectric constant increase than pure PVDF. It can

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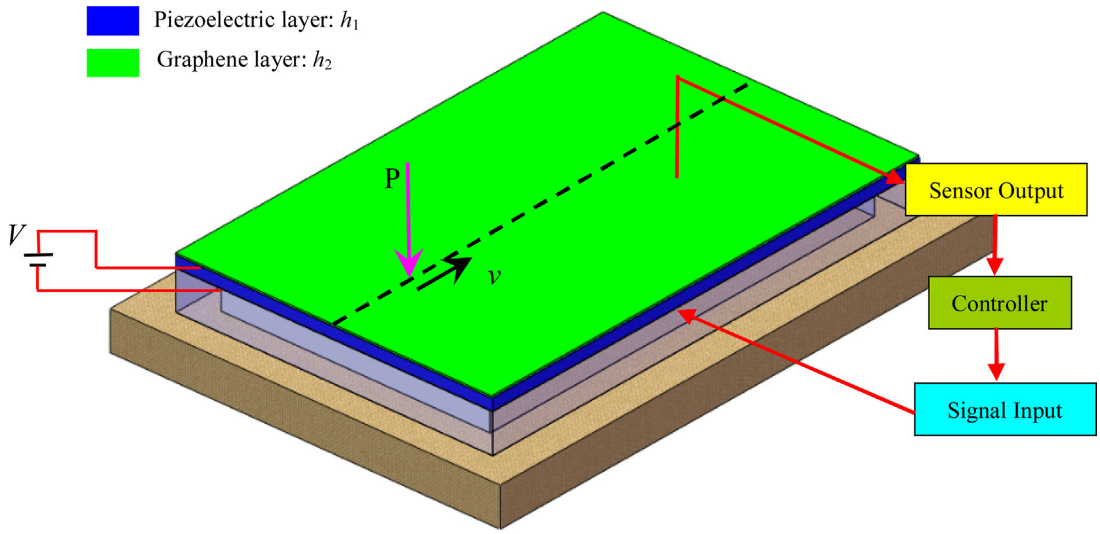

Fig. 1. The schematic of a GP laminated thin plates based nano-sensor in sensing a moving load.

be envisaged that the emerging of graphene/piezoelectric composites will trigger a wave of research on the GP based electrical elements or devises in the near future.

It is well known that the sensing principles of sensors are detecting some related physic signals including force, optics, magnetic, electricity, thermo, displacement, frequency, etc, which can be converted into electronic signals. As to graphene based nano-sensors, most works are focused on the dynamic characteristics represented by resonant frequencies. As early as 2005, Kitipornchai et al. [24] reported the vibration response of multilayered graphene sheets with a continuum model, and predicted the van der Waals interaction between two layers which had significant influences on higher natural frequencies. Then nonlocal elasticity theory containing the long range forces among atoms was introduced to study the mechanical characteristics of graphene and carbon nanotubes in literatures [25–29]. Murmu and Pradhan [25] studied the vibration characteristic of single-layered graphene sheets (SLGS) embedded in an elastic medium. At the same time, Pradhan and Kumar [26] also demonstrated the vibration analysis of SLGS embedded in an elastic medium, but the graphene was taken as a type of orthotropic material. And Ansari et al. [27] investigated the vibration behavior of multilayered graphene sheets under different boundary conditions. Moreover, molecular dynamics (MD) method is also an effective instrument to study the vibration characteristics of graphene. Ansari et al. [30] compared the linear resonant frequencies obtained by nonlocal elasticity and MD, which showed a good agreement by fitting the scale coefficients. Shen et al. [31] presented the nonlinear transverse vibration response of bilayer graphene sheets in thermal environment with nonlocal elasticity and MD simulations, and investigated the nonlinear bending behaviors of SLGS in thermal environment in another work [32]. Then Kang et al. [33] demonstrated the molecular dynamics simulation on the fundamental resonant frequency of a tunable graphene based resonators by adding tension on the boundary, then a series of works were presented to discuss its vibration characteristics of SLGS at various conditions [34,35]. Further, molecular dynamics was used by Arash et al. [36] to analyze SLGS as mass sensors in detecting noble gases by detecting frequency shifts. However, to the best knowledge of authors, only a few of works [37,38] have paid attention to the importance of graphene/piezoelectric laminated films theoretically, and much more efforts are needed, especially the nonlinear dynamic responses of GP based laminates under dynamic loads.

Motivated by the above considerations, the scale-dependent nonlinear dynamic problems of GP-based nano-sensor under a moving load induced by the external moving adhesive particles or molecules are investigated based on the nonlocal elasticity theory. The scale-dependent nonlinear dynamic equations induced by Von Kármán nonlinear geometric relations is firstly derived by utilizing the Hamilton's principles and Galerkin method in Section 2. Then a reformulated DQM is introduced to solve the nonlinear dynamic equations in Section 3. In Section 4, several examples are firstly presented to validate the accuracy and convergence of present methods. Next, the effects of some key parameters, such as the magnitude and velocity of moving load, the external linear voltage, nonlocal parameter, and the thickness of piezoelectric layer on the scale-dependent nonlinear dynamic characteristics of GP-based nano-sensor are described. Results show that the moving velocity of dynamic load plays a significant role, and it mainly manifest in that the central maximum deflection varies in a fluctuating trend with moving velocity increases, the geometrical nonlinearity should be paid much attention in analyzing relative large deflection problems of GP laminated films, and the external voltage exerted on piezoelectric layer will increase the maximum of central deflection during forced vibration. The meaningful results can serve as references for the design of a nano-sensor or other GP-based electromechanical devices.

2. Nonlinear dynamic equations of GP laminated films under moving load

A graphene/piezoelectric laminated films based nano-sensor with dimension $a \times b$ and thickness $h = h_1 + h_2$ in a Cartesian coordinate system (x, y, z) is shown in Fig. 1, where the graphene layer (h_2) is deposited on the upper surface of the piezoelectric layer (h_1). And the moving load $p(x, y, t)$ induced by the external moving adhesive particles or molecules at constant velocity v is written as [39]

$$p(x, y, t) = \sum_{i=1}^{N} P_i(t)\delta(x - x_i)\delta(y - y_i)U_i(t) \quad (1)$$