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Transverse impact analysis of double-layered graphene sheets on an elastic foundation

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ABSTRACT

In using graphene sheets (GSs) to design nanoscale devices or nanostructure elements, it is very important to understand the properties of these elements against various mechanical loading conditions. The aim of this study is to investigate the impact response of double layer graphene sheets (DLGSs) on elastic foundations when they are subjected to low-velocity impact by nanoparticles. The analytical model is based on general continuum mechanics theory, which considers that a layer stack of two individual GSs is bound together by van der Waals (vdW) forces, and the interaction of DLGSs embedded to elastic foundations is modeled based on the Winkler model. The result shows that elastic foundation materials have a significant effect on the impact characteristics of GSs. The impact response of GSs subjected to nanomass has exceedingly short times with picoseconds order. This investigation may be helpful in engineering design of using GSs as nanostructure elements for nanoelectromechanical system (NEMS).

1. Introduction

Graphene sheets (GSs) have attracted a great deal of research attention due to their extraordinary mechanical and physical properties (Frank, Tanenbauma, van der Zande, & McEuen, 2007; Castro Neto, Guinea, Peres, Novoselov, & Geim, 2009; Lee et al., 2013; Novoselov et al., 2004). The fascinating carbon materials have many applications, including to the reinforced material and the solar cells (Potts, Dreyer, Bielawski, & Ruoff, 2011; Roy-Mayhew & Aksay, 2014). Especially, GSs have found their way into nanoelectromechanical system (NEMS) due to very small dimension and the interesting properties, such as nanomechanical resonators, biosensor and sensitive mass detection (Chen et al., 2009; Schedin et al., 2007; Arash, Jiang, & Rabczuk, 2015). Scott Bunch et al. (2007) has reported that GSs were taken into account for serving as nanoresonators. The vibrations of GSs with fundamental resonant frequencies in the megahertz range can be actuated either optically or electrically, and detected optically by interferometry. The application of graphene NEMS has extended beyond just mechanical resonators. The graphene-based NEMS resonators provided higher sensitivity as nanomechanical mass sensor. The operation of a NEMS mass sensor relied on monitoring how the resonance frequency of a nanomechanical resonator changed when an additional nanomass was adsorbed onto its surface (Chaste et al., 2012; Eichler et al., 2011; Pang et al., 2006; Natsuki, Shi, & Ni, 2013). Natsuki et al. (2013) investigated the influences of the attached mass and position of the nanoparticles on the frequency shifts of double-layered graphene sheets (DLGSs) using the continuum elasticity theory. The result showed that the frequency shifts of DLGSs were much higher than those of single-layered graphene sheets (SLGSs). DLGSs based

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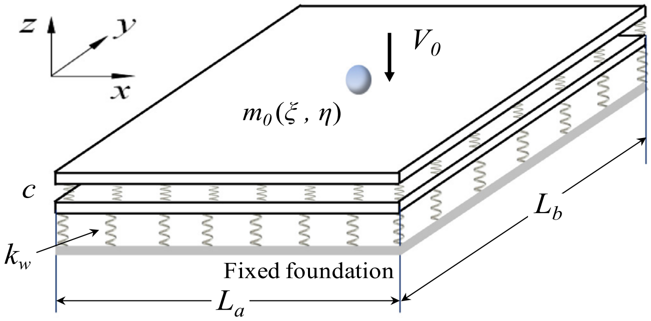

Fig. 1. Model schematic diagram of double-layered graphene sheets embedded in elastic foundation.

nanomechanical resonator could provide higher sensitivity than SLGSs. The graphene-based nanomechanical resonator could supply a high mass sensitivity and reached at least zg (10^{-21} kg) unit (Natsuki et al., 2013; Ekinci, Huang, & Roukes, 2004). The potential of using GSs as the sound insulating materials in nano-device was also investigated, showing that the sound transmission loss is very high in the multi-layered GSs (Natsuki & Ni, 2014). GSs appear to be excellent element materials for nanostructures of NEMS because of extremely small size and dynamic mechanical property.

Nanoelectromechanical system can be designed and characterized by understanding the mechanical, electrical, and energy properties of GSs. Up to now, many studies on the mechanical property of GSs have been carried out by both theoretical and experimental methods (Frank et al., 2007; Lee, Wei, Kysar, & Hone, 2008; Shi, Natsuki, Lei, & Ni, 2014; Jiang, Wang, & Li, 2009). The static and dynamic measurements for the mechanical properties of stacks of suspended GSs were performed using atomic force microscopy (AFM) (Frank et al., 2007; Lee et al., 2008). The equivalent Young's modulus and the thickness, which are the two major material constants of GSs, have been obtained based on the continuum mechanical model (Shi et al., 2014). The result provided a critical link between the fundamental science of graphene and its engineering applications. The elastic instability of GSs was investigated using atomistic finite element approaches (Chandr, Chowdhury, Adhikari, & Scarpa, 2011), continuum mechanics theory (Shi, Ni, Lei & Natsuki, 2011; Natsuki, Shi, & Ni, 2012), and molecular dynamics (MD) simulations (Sgouros, Kalosakas, Galiotis, & Papagelis, 2016). These investigations would be helpful in designing the mechanical sensors and graphene-based electrochemical sensors. Some investigation has also focused on the vibration frequency of graphene resonator, showing the result that its resonant frequency can over terahertz range, which may help to fulfill potential applications of GSs such as nanosensors, nanotransistors and other NEMS (Jalali & Naei, 2014; Natsuki et al., 2013; Sakhaee-Pour, Ahmadiana, & Naghdabadi, 2008; Kitipornchai, He & Liew, 2005).

Graphene sheets (GSs) as nanoplates can be promising materials for the next generation of nano electro-mechanics system (NMES). Especially, GSs were found to have potential application in nanoscale electronic devices and nano sensors in which GSs are usually coated on substrates, such as silicon and aluminum oxide, instead of being suspended (Mercana, Demira, Akgoza, & Civaleka, 2015; Motaghiana, Mofida, & Alanjari, 2011; Zhang, Zhang, Liew, & Yu, 2016; Fadaee, 2016). A Winkler model can be adopted to deal with the mechanical property of substrates considered to be an elastic medium foundation (Motaghiana et al., 2011; Samaei, Aliha, & Mirsayar, 2015). GSs can offer potential of achieving ultrahigh sensitivity in detection of nanoparticles. The vibration frequency of GSs will change due to the added nanoparticles when an external nanoparticle is attached to the GSs due to hitting. It is important to investigate the impact behaviors of nanoparticles on the surface of GSs. The impact response of nanoparticles on GSs still remains. Up to now, there has been few research on the impact response of GSs subjected to nanoparticles (Natsuki & Ni, 2016). In this study, a theoretical approach was proposed to investigate the impact force-time history of DLGSs on elastic foundations when subjected to low-velocity impact load. The DLGSs were considered as crystal structure with stacked layers of atomic layers that are bound together through van der Waals (vdW) forces. Moreover, the Winkler foundation was presented to model the interaction between the graphene sheets and the elastic foundations, so as to easily obtain a set of governing equations and develop a closed form solution. The numerical simulation and discussion, including the effects of the elastic medium materials, the impact velocity and the energy absorption on the impact response of GSs, were carried out by using the present theoretical method.

2. Theoretical approach

As shown in Fig. 1, DLGSs on an elastic foundation are regarded as that the neighboring layers are coupled by vdW interaction forces and the elastic foundation is described by a Winkle spring model. In this simulation, DLGSs are modeled as a stack of two individual graphene sheet with each thickness of h, the x- and y-axes are taken along the length L_a and width L_b, respectively. The coordinate w is taken along the thickness direction of the GSs. The origin is taken at one corner of the mid-plane of each graphene sheet. According to continuum mechanics theory, the governing equations of motion for