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Investigations on structural intensity in nanoplates with thermal load

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ABSTRACT

The finite element method (FEM) based on the nonlocal Kirchhoff plate theory with second order strain gradient is developed to derive the dynamic equations of nanoplate under thermal load with the small scale effect taken into consideration. The characteristics of transmission and distribution of the steady-state energy flows in the rectangular nanoplate are analyzed based on the structural intensity approach. In the numerical calculation, the natural frequencies of single layer graphene sheets (SLGS) computed by nonlocal FEM agree well with theoretical results of nonlocal strain gradient plate theory, which validate the reliability of the present method. The effects of nonlocal parameters, mechanical load and thermal load on structural intensity are considered. It can be found that the small scale effect is not same for different applying positions and excitation frequencies. The influence of mechanical load on vibration energy flow paths may be cancelled by thermal load, and the effect of thermal load on vibration energy flow paths also may be cancelled by mechanical load. The critical thermal load may be found to determine whether thermal load play a more important role in form energy flow of SLGS than mechanical load.

1. Introduction

Nanoscale structures i.e., single layer graphene or nanoplates have unique electronic properties and superior mechanical properties [1]. Many potential applications of nanostructures in nanoresonators, nanosensors and nanoelectromechanical systems are based on their vibration characteristics [2–6]. Structural vibration is related with the energy flow which mainly results from external load, such as thermal load and mechanical load. At the same time, the graphene also exhibits its good energy dissipation characteristics, and may be made the single layer graphene heat dissipation film [7,8]. In order to control structural vibration or improve energy dissipation characteristics, transmission and distribution of energy flow in a nanostructure are desired. The structural intensity approach is used to describe distribution of energy flow in the nanostructure here.

Generally, atomistic modeling and nonlocal continuum modeling are developed to analyze nanoplates. Nonlocal continuum modeling is less computationally expensive than the atomistic modeling, and in good agreement with atomistic modeling. Nonlocal elasticity mechanics theory can be effectively employed to investigate vibration characteristics of nanoplates. Pradhan and Phadikar [9] investigated double layered nanoplates based on the Eringen's nonlocal continuum mechanics theory. Ansari et al. [10] used general differential quadrature method to analyze vibration of single-layered graphene sheets based on the Eringen's plate theory. Aksencer and Aydogdu [11] used Navier type solution method to study forced vibration of nanoplates based on the Eringen's plate theory. Zhou et al. [12] used a rigorous analytical symplectric method to study double layered orthotropic nanoplate based on the Eringen's plate theory. At the same time, nonlocal strain gradient theory taken into consideration is also usually used to investigate nanostructure [13–25]. Papargyri-Beskou research team [15–17] analyzed the dynamics of the beam and plate based on the strain gradient theory, and these results may correctly describe dynamics behavior of nanostructure systems. In order to describe the effect of the nanostructure on mechanical properties, it is assumed that nanostructure is made of nonlocal elastic material, where the stress state at a given reference point depends not only on the strain of this point, but also on the higher order gradient of strain so as to with the influence of the long range forces of all other atoms. So strain gradient theory may be regarded as a kind of nonlocal continuum mechanics theory. Wang and Hu [18] studied flexural wave propagation in single-wall carbon nanotubes based on the nonlocal beam theory with second order strain gradient, and drew significant conclusions. Shahriari et al. [21] analyzed the vibration of composite nanoplates using Mindlin's strain gradient theory. Farajpour et al. [23] developed a new size-dependent plate model based on the nonlocal strain gradient theory. Ebrahimi and Dabbagh [25] analyze the wave propagation response of magneto-electro-elastic nanoplates via nonlocal strain gradient theory. Finite element method (FEM) is more useful for complex structure [26–28]. Obviously, vibration characteristics of the nanoplate

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structures have been studied in detail. However, to our knowledge, no work on the structural intensity of nanoplate structures has been published.

In the present work, the nonlocal Kirchhoff plate theory is used to describe the motion of the graphene sheets. The frequency responses of single layer graphene sheets are researched by the nonlocal FEM. The structural intensity of the nanoplate structure with thermal load is investigated by the nonlocal strain gradient theory. The structural intensity formulations for nanoplate with thermal load are obtained by structural intensity approach. Furthermore, the effects of nonlocal parameters, mechanical load and thermal load on structural intensity are also investigated. It can be seen that thermal load play an important role on making vibration energy flow patterns.

2. The constitutive law of the nanoplate structure with thermal load

Thermoelastic strain-stress relations of the thin plate are expressed as based on the Kirchhoff plate theory [29]

$$\sigma_x = \frac{E}{1-\mu^2}(\varepsilon_x + \mu\varepsilon_y) - \frac{E\alpha T}{1-\mu}, \tag{1}$$

$$\sigma_y = \frac{E}{1-\mu^2}(\varepsilon_y + \mu\varepsilon_x) - \frac{E\alpha T}{1-\mu}, \tag{2}$$

$$\tau_{xy} = \tau_{yx} = G\varepsilon_{xy} \tag{3}$$

where ε_x and ε_y are normal strains parallel to the x and y axes, respectively, γ_{xy} the shear strain in the xy plane. E denotes Young's modulus, μ Poisson's ratio, $G = \frac{E}{2(1+\mu)}$, α linear thermal expansion coefficient, and $T(x, y, z)$ the temperature rise of any point in the plate.

The strain gradient elastic theory assumes that the stress at a point is a function of both strain and strain gradient at the same point, the second-order strain gradient constitutive equation link with the microstructures can be expressed as [14,26]

$$\sigma_{ij} = C_{ijkl}(\varepsilon_{kl} + g^2\nabla^2\varepsilon_{kl}), \tag{4}$$

where σ_{ij} is the stress tensor, C_{ijkl} is the elastic tensor, ε_{kl} is the strain tensor and g is the nonlocal material parameter.

The second order strain gradient constitutive equation for the nanoplate structures under thermal load may be expressed as

$$\sigma_x = \frac{E}{1-\mu^2}(\varepsilon_x + \mu\varepsilon_y) + g^2\frac{E}{1-\mu^2}\nabla^2(\varepsilon_x + \mu\varepsilon_y) - \frac{E\alpha T}{1-\mu}, \tag{5}$$

$$\sigma_y = \frac{E}{1-\mu^2}(\varepsilon_y + \mu\varepsilon_x) + g^2\frac{E}{1-\mu^2}\nabla^2(\varepsilon_y + \mu\varepsilon_x) - \frac{E\alpha T}{1-\mu}, \tag{6}$$

$$\sigma_{xy} = G\varepsilon_{xy} + g^2 G\nabla^2\varepsilon_{xy}, \tag{7}$$

where nonlocal parameter g is a material parameter to reflect the effects of microstructures on the stress in the nonlocal elastic material and given by Refs. [14,20]

$$g = \frac{d}{\sqrt{12}}, \tag{8}$$

where d is the axial distance between two particles in the material.

Integrating along the nanoplate thickness direction, membrane forces, bending moments and shear forces may be given based on strain gradient elasticity.

$$M_x = -D\left(\frac{\partial^2 w}{\partial x^2} + \mu\frac{\partial^2 w}{\partial y^2}\right) - g^2 D\nabla^2\left(\frac{\partial^2 w}{\partial x^2} + \mu\frac{\partial^2 w}{\partial y^2}\right) - M_T, \tag{9}$$

$$M_y = -D\left(\frac{\partial^2 w}{\partial y^2} + \mu\frac{\partial^2 w}{\partial x^2}\right) - g^2 D\nabla^2\left(\frac{\partial^2 w}{\partial y^2} + \mu\frac{\partial^2 w}{\partial x^2}\right) - M_T, \tag{10}$$

Table 1
Material properties.

Materials	Yong's modulus E(Gpa)	poisson's ratio μ	Density ρ(kg/m^3)
Graphene	1000	0.30	2237

Table 2
The natural frequencies (THz) of SLGS with simply supports.

Mode	Analytical results	Nonlocal FEM
(1,1)	0.0683	0.0682
(1,2)	0.1708	0.1701
(2,2)	0.2732	0.2709
(1,3)	0.3415	0.3393
(2,3)	0.4439	0.4382
(3,3)	0.6144	0.6026

$$M_{xy} = M_{yx} = -D(1-\mu)\frac{\partial^2 w}{\partial x\partial y} - g^2 D(1-\mu)\nabla^2\left(\frac{\partial^2 w}{\partial x\partial y}\right), \tag{11}$$

$$N_x = -\frac{Eh}{1-\mu^2}\left(\frac{\partial^2 w}{\partial x^2} + \mu\frac{\partial^2 w}{\partial y^2}\right) - g^2\frac{Eh}{1-\mu^2}\nabla^2\left(\frac{\partial^2 w}{\partial x^2} + \mu\frac{\partial^2 w}{\partial y^2}\right) - N_T, \tag{12}$$

$$N_y = -\frac{Eh}{1-\mu^2}\left(\frac{\partial^2 w}{\partial y^2} + \mu\frac{\partial^2 w}{\partial x^2}\right) - g^2\frac{Eh}{1-\mu^2}\nabla^2\left(\frac{\partial^2 w}{\partial y^2} + \mu\frac{\partial^2 w}{\partial x^2}\right) - N_T, \tag{13}$$

$$N_{xy} = -\frac{Eh}{(1+\mu)}\frac{\partial^2 w}{\partial x\partial y} - g^2\frac{Eh}{(1+\mu)}\nabla^2\left(\frac{\partial^2 w}{\partial x\partial y}\right), \tag{14}$$

$$\begin{aligned} Q_x &= -D\left(\frac{\partial^3 w}{\partial x^3} + \frac{\partial^3 w}{\partial x\partial y^2}\right) - g^2 D\nabla^2\left(\frac{\partial^3 w}{\partial x^3} + \frac{\partial^3 w}{\partial x\partial y^2}\right) - \frac{\partial M_T}{\partial x} \\ &= -D\frac{\partial}{\partial x}\nabla^2 w - g^2 D\frac{\partial}{\partial x}\nabla^2\nabla^2 w - \frac{\partial M_T}{\partial x}, \end{aligned} \tag{15}$$

$$\begin{aligned} Q_y &= -D\left(\frac{\partial^3 w}{\partial y^3} + \frac{\partial^3 w}{\partial x^2\partial y}\right) - g^2 D\nabla^2\left(\frac{\partial^3 w}{\partial y^3} + \frac{\partial^3 w}{\partial x^2\partial y}\right) - \frac{\partial M_T}{\partial y} \\ &= -D\frac{\partial}{\partial y}\nabla^2 w - g^2 D\frac{\partial}{\partial y}\nabla^2\nabla^2 w - \frac{\partial M_T}{\partial y}, \end{aligned} \tag{16}$$

where $M_T = \frac{E\alpha}{1-\mu}\int_{-h/2}^{h/2} Tzdz$ is equivalent bending moment of T, $N_T = \frac{E\alpha}{1-\mu}\int_{-h/2}^{h/2} Tdz$ equivalent membrane force of T, $D = Eh^3/12(1-\mu^2)$, h the thickness of the nanoplate. Obviously, T varies through the thickness of the plate, or else $M_T = 0$.

3. Finite element model of the nanoplate structure with thermal load

Lagrange's equations are used to build finite element model of strain gradient Kirchhoff plate with thermal load, and then the FEM based on the nonlocal Kirchhoff plate theory with second order strain gradient is developed to derive the dynamic equations of nanoplate with thermal load.

Eqs (5)–(7) can be written in matrix form as

$$\boldsymbol{\sigma} = (1 + g^2\nabla^2)\boldsymbol{D}\boldsymbol{\varepsilon} + \boldsymbol{\sigma_T}, \tag{17}$$

where $\boldsymbol{\sigma} = [\sigma_x \ \ \sigma_y \ \ \sigma_{xy}]^{\mathrm{T}}$, $\boldsymbol{\varepsilon} = [\varepsilon_x \ \ \varepsilon_y \ \ \varepsilon_{xy}]^{\mathrm{T}}$, $\boldsymbol{\sigma_T} = \left[-\frac{E\alpha T}{1-\mu} \ \ -\frac{E\alpha T}{1-\mu} \ \ 0\right]^{\mathrm{T}}$ and $\boldsymbol{D}$ is the elastic coefficients matrix given by

$$\boldsymbol{D} = \frac{E}{1-\mu^2}\begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & (1-\mu)/2 \end{bmatrix}. \tag{18}$$

So, element potential energy may be obtained by use of stress-strain

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