



A refined nonlocal thermoelasticity theory for the vibration of nanobeams induced by ramp-type heating



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ABSTRACT

For small volumes at the micrometer and nanometer level, classical continuum mechanics cannot be used to capture experimentally observed phenomena, such as size effects. Moreover, dissipation is much less pronounced than that in the case of macroscopic volume elements. To remedy the situation, generalized continuum mechanics theories should be used as an alternative to molecular dynamics simulations which do provide physical insight, but may not be suitable for engineering applications and the formulation of related boundary value problems. The present contribution is an example in this direction. An Euler–Bernoulli beam model is constructed to study the vibration of a nanobeam subjected to ramp-type heating. A generalized thermoelasticity theory with non-local deformation effects and dual-phase-lag (DPL) or time-delay thermal effects is used to address this problem. An analytical technique based on Laplace transform is employed. The inverse of Laplace transform is computed numerically using Fourier expansion techniques. The effects of nonlocality, DPLs, and the ramping-time parameter on the lateral vibration, the temperature, the displacement and the flexural moment of the nanobeam are discussed. The results are shown quantitatively in corresponding graphs.

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1. Introduction

The theory of coupled thermoelasticity has been extended by Lord and Shulman [1], as well as Green and Lindsay [2] to include a thermal relaxation time in the constitutive relations. The extension to the anisotropic case has been established by Dhaliwal and Sherief [3]. Green and Naghdi [4] proposed a new generalized thermoelasticity theory by including the thermal-displacement gradient among the independent constitutive variables. An important feature of this theory, which is not present in other thermoelasticity theories, is that it does not accommodate dissipation of thermal energy.

The dual-phase-lag (DPL) model describes the interactions between phonons and electrons that occur on a microscopic level and act as retarding sources causing a delayed response on the macroscopic scale [5,6]. This results to a modification of the standard thermoelastic model where the classical Fourier law is replaced by a non-classical one involving two different

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time translations (time-delay parameters): a phase-lag (PL) for the heat flux τ_q and a PL for the temperature gradient τ_θ . The physical meaning and related experimental evidence for this modification have been established [7]. A Taylor series approximation of the aforementioned modified Fourier law (together with the remaining field equations) leads to a complete system of equations describing the DPL thermoelastic model. This model allows for the transmission of thermoelastic disturbances in a wave-like manner if the approximation is linear with respect to τ_q and τ_θ ($0 \leq \tau_\theta < \tau_q$) or quadratic in τ_q and linear in τ_θ ($\tau_q > 0$ and $\tau_\theta > 0$). Thus, the theory is able to incorporate thermal pulse transmissions in a very logical manner. Abouelregal and Abo-Dahab [8] studied the induced displacement, temperature and stress fields in an infinite non-homogeneous elastic medium with a spherical cavity, in this context. Abouelregal [9] applied the DPL heat transfer model for an isotropic solid sphere. The solution of the problem is carried out when the boundary of the sphere is maintained at constant heat flux and the displacement of the surface is constrained. Such generalized considerations for modeling the thermoelastic response of materials and structures seem to have become important recently in the fields of microtechnology and nanotechnology. In fact, micro/nano beams are now used as basic structural elements for new advanced devices of decreasing size, as is briefly discussed below.

Micro-scale mechanical resonators are characterized by high sensitivity and fast response, and are widely used as sensors and modulators. Nano-scale resonators have also attracted considerable attention recently due to their ever increasing and promising nanotechnology-related applications. Accurate analysis of various effects on the characteristics of resonators, such as resonant frequencies and quality factors, is crucial for designing high-performance nanoscale components. Many authors have studied the vibration and heat transfer process of beams (e.g. Fang et al. [10], Huniti et al. [11]). Kidawa [12] considered the problem of transverse vibrations of a beam induced by a mobile heat source, and provided an analytical solution using the Green's function method. Boley [13] analyzed the vibrations of a simply-supported rectangular beam subjected to a suddenly applied heat input distributed along its span. Manolis and Beskos [14] examined the thermally induced vibration of structures consisting of beams and exposed to rapid surface heating. They have also studied the effects of damping and axial loads on the structural response.

Nonlocal beam models have received increasing interest in the past few years. Nonlocal continuum mechanics theories regard the stress state at a point as a function of the strain state in all points of the body, while classical continuum mechanics assumes that the stress state at a given point is dependent uniquely on the strain state at that same point. Eringen's nonlocal elasticity theory [15], was developed in an effort to deal with this situation. Small length scale effects are accounted for by incorporating an internal characteristic length, e.g. the length of the atomic bond (C–C bond for carbon materials) into the stress–strain relationship. The dispersion curves of the nonlocal model are in excellent agreement with those of the Born–Karman theory of lattice dynamics; the dislocation core and cohesive stress predicted by the nonlocal theory are close to those known in the physics of solids [16,17].

Among all nano-objects, the mechanical behavior of nanotubes and nanobeams have been most widely investigated by using this nonlocal theory. Peddieson et al. [18] illustrated how in the Bernoulli–Euler beam model, small scale effects manifest themselves in the range of nano-meters. Sudak [19] applied nonlocal elasticity to study axial buckling of carbon nanotubes. Since then, a large number of researchers [20] have applied nonlocal continuum theories to model carbon nanotubes or nanobeam-like structures. Duan and Wang [21] conducted a bending analysis of circular graphene sheets based on nonlocal elasticity theory.

The basic difference between classical and nonlocal elasticity theory [22] lies on the definition of stress. In classical elasticity, the stress at a point is a function of strain at that point only, whereas in nonlocal elasticity, the stress at any point is a function of strains at all other points of the continuum. Hence, the nonlocal theory contains information about long range forces of atoms or molecules and, thus, an internal length scale parameter should be introduced in the formulation. An alternative size-dependent elasticity theory which was directly motivated by deformation processes at the nanoscale is Aifantis one-internal length parameter gradient theory of elasticity (GRADELA). Since its original publication in 1992 [23], a number of articles (e.g. [24–31] and references quoted therein) have been published showing how GRADELA can eliminate stress/strain singularities from dislocation cores and crack tips, how it can be used to interpret size effects, and also model wave dispersion, in agreement with experiments. The relation between generalized gradient elasticity theory (involving the Laplacians of both stress and strain) and Eringen's nonlocal elasticity theory has been dealt with in [31]. In this connection, Aifantis' original GRADELA model is a strain gradient theory, whereas Eringen's model is a stress gradient theory.

In the present paper, the vibration of a nanobeam resonator induced by a ramp-type heating is addressed within the framework of a nonlocal (or stress gradient) thermoelasticity theory with DPL thermal effects. The Laplace transform method is used to determine the lateral vibration, the temperature, the displacement and the bending moment of the nanobeam. The effects due to nonlocality, phase lags and the ramping time parameter are studied. Numerical results are also presented to illustrate the influence of these factors on the vibrational response of the nanobeam resonator.

2. The nonlocal DPL thermoelastic model

According to Eringen's nonlocal elasticity theory [22], the stress at any reference point in the body depends not only on the strain at this point but also on the strain at all points of the body. The relevant constitutive equation of nonlocal elasticity for homogenous and isotropic elastic solids reads

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