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Thermoelastic damping in a nonlocal nano-beam resonator as NEMS based on the type III of Green–Naghdi theory (with energy dissipation)

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ABSTRACT

In this paper, thermoelastic damping in a nano-beam is studied employing the type III of Green–Naghdi (GN) theory (with energy dissipation). The nano-beam is considered as a beam-type of NEMS (nano-electro-mechanical systems). A nonlocal Euler–Bernoulli beam model is established based on the theory of nonlocal elasticity and the small scale effect is taken into consideration in the former theory. A hybrid numerical method based on the Galerkin finite element formulation and Newmark finite difference method is used to solve the derived governing equations. The presented formulations are valid for both types II and III of GN theory of generalized coupled thermoelasticity in NEMS and MEMS (micro-electro-mechanical systems). The obtained results for type II of GN theory (without energy dissipation) are validated by the existing analytical results in the literature to verify the presented method and results. To show the effects of thermoelastic damping on dynamic behaviors of thermoelastic field in NEMS, the type III of GN theory is investigated in the paper. The responses of nano-beam resonator in lateral deflection, temperature and stress fields considering simply supported conditions are obtained and shown as functions of length and time. Also, the effect of different loading parameters on the transient thermoelastic behaviors is studied in both types II and III in GN theory. The corresponding dynamic properties are presented, which are shown to be very different from those predicted by classic elasticity theory when nonlocal effects are significant.

1. Introduction

Micro-electro-mechanical systems attract the attention in the 1980s as sensors and actuators. The fact that they could be manufactured using current production techniques and infrastructure of the semiconductor industry means that they could be produced at low expense and in large volumes. Their light weight, small size, low-energy consumption and stability made them even more attractive. In recent years, the field of MEMS has grown quickly and used into many applications such as accelerometers, pressure sensors, inkjet printers, gyroscopes, etc. Nowadays, current technological challenges require more and more reduced sizes. The next process of miniaturization is called nano-electro-mechanical systems. For transiting from MEMS to NEMS needs much reconsideration concerning the sensing techniques. Besides, for compensating the loss of performances when sensors are scaled down to the NEMS level, the resonant sensing has been widely implemented in nano-sensors. Typical MEMS/NEMS structures consist of arrays of thin beams in the order of micro/nano-scale. MEMS/NEMS are very small devices in which electric as well as mechanical, thermal and fluid phenomena appear and interact. Because of their micro/nano-scale, strong coupling effects arise between the different forces, which were disregard at macroscopic scale, must be taken into account. In order to accurately design such micro/nano-electro-mechanical systems, it is important to handle the coupling between the thermal and mechanical fields [1–6].

There are two principal sources of energy loss in MEMS/NEMS, which can be classified into intrinsic loss and external loss [7]. The intrinsic loss includes internal friction, thermoelastic effects, etc. The external loss includes air damping, support loss also called anchor losses, squeeze film damping, etc. Thermoelastic damping is a significant loss mechanism near room temperature in MEMS/NEMS, working under vacuum condition. Zener [8] derived an expression for the energy loss in a thin beam. To study the thermoelastic damping in MEMS and NEMS, some researchers used the classical theory of coupled thermoelasticity in which the wave propagation speed is considered to be infinite. Some research works based on the classical theory of coupled thermoelasticity are reviewed as follows:

Lifshitz and Roukes [9] provided an exact expression for thermoelastic damping of small flexural vibrations in micro/nano-thin beams without any simplifications considered by Zener [8] Prabhakar et al. [10] studied thermoelastic damping in micromechanical resonators with two-dimensional heat conduction. Kunzig et al. [11] presented

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the effect of thermoelastic damping on the total Q-factor (quality factor) in state of the art MEMS gyroscopes with complex beam like suspensions. Vahdat and Rezazadeh [12] discussed the effects of axial and residual stresses on thermoelastic damping in capacitive micro-beam resonators. Rezazadeh et al. [13] studied thermoelastic damping in micro-beam resonators by using the modified couple stress theory. Tunvir et al. [14] analyzed the effect of cross-sectional shape on thermoelastic dissipation energy of micro/nano-elastic beams. Guo et al. [15] used the finite element method to investigate the effects of geometric parameters of the vented beam on thermoelastic energy loss in clamped–clamped and clamped-free beam resonators.

The classical theories of coupled thermoelasticity predict an infinite speed for the propagation of thermal and elastic waves, which is not the realistic assumption. To this end, the non-classical theories of coupled thermoelasticity have been developed to simulate the wave propagations with finite speed. The non-classical theories admit a finite speed for the propagation of thermal waves through the continuum, which are called the second sound theories. Lord and Shulman [16] developed the theory of generalized thermoelasticity with one relaxation time for the special case of an isotropic body. Green and Lindsay [17] developed the theory of thermoelasticity by taking two relaxation times.

One of the most important coupled thermoelasticity theories was presented by Green and Naghdi as GN theory in which the propagation of thermoelastic waves was modeled in a domain with high-rate excitation [18–20]. The GN theory of coupled thermoelasticity provides sufficient basic modifications in the constitutive equations that permit treatment of a much wider class of heat flow problems, called as types I (classical theory), type II (without energy dissipation) and type III (with energy dissipation). Thermal wave propagation with finite speed can be modeled by types II and III. The type II does not contain dissipation of thermal energy. The constitutive equations in the GN theory of type III consider energy dissipation [21]. In some research works, the GN theory was used to study the coupled thermoelasticity of macro-structures. The thermoelastic wave propagation in FG thick hollow cylinder was studied using the hybrid numerical method for infinite cylinder [22], finite cylinder [23] and also using the analytical method [24].

Sun et al. [25] studied the importance of thermoelastic damping in micro-beam resonators by the Lord and Shulman theory of generalized thermoelasticity. Sharma and Grover [26] analyzed thermoelastic vibrations by the Lord and Shulman theory in micro-/nano-scale beam resonators. Quintanilla [27] proposed a model of the thermoelasticity based on the GN theory of type II (without energy dissipation) for microstructure. Guo et al. [28] derived an explicit formula of thermoelastic damping in micro-/nano-mechanical resonators based on dual-phase-lagging generalized thermoelasticity theory.

The Euler–Bernoulli beam theory is not an accurate theory for simulating the behaviors of micro-/nano-beam. The nonlocal theory in continuum mechanics was developed by some researchers such as Eringen [29] and Edelen [30] to model the small scale effects. To do this, the stress state is specified at a given point as a function of the strain states at all points in the structures. The presented nonlocal theory is based on the forces between atoms and the internal length scale, which are considered in the constitutive equations as a material parameter. There are some research works in which the nonlocal theory of elasticity has been employed for analysis of bending, buckling and vibration analyses of beam-like elements in micro-electro-mechanical or nano-electro-mechanical devices (see for example [31–33]).

Tang et al. [34] presented two research works as two parts on the evaluation of length-scale factors in dynamic analysis of MEMS and NEMS. In part one of their works, the experimental determination of length-scale factors for micro- and nano-sized silicon cantilevers, which the length-scale factor improves the accuracy of the employed models [34]. The micro- and nano-sized length-scale factors were estimated using experimental data collected from nano-indentation and micro-indentation experiments [34]. In part two of their works, the tip deflections were estimated employing the conventional tip deflection model and the modified deflection model considering the length-scale factor. Then, the obtained deflections were compared with the experimental data [35]. A novel automated torsion balance technique was employed to investigate the size dependence in the torsional response of micro-sized polycrystalline copper wires using some experiments by Liu et al. [36]. In another work, the torsion balance technique was successfully used to investigate the analysis of the plasticity of micron scale Cu and Au wires under cyclic torsion by Liu et al. [37].

The aim of this paper is the application of GN theory of coupled thermoelasticity with nonlocal theory to study the thermoelastic damping in nano-/micro-electro-mechanical systems. The nonlocal theory is employed to simulate the small scale effects on the obtained results. Both types II and III of the GN theory are considered in the problem. The thermoelastic governing equations are derived for a nano-beam resonator subjected to thermal shock loading. A hybrid numerical method based on the Galerkin finite element (GFE) method and Newmark finite difference (NFD) method is employed to solve the governing equations. The presented method and obtained results are verified with reported data in the published literature based on the type II of GN theory. The dynamic responses of nano-beam resonator in lateral deflection, temperature and stress fields under simply supported conditions are obtained and shown in time domain. The effects of thermoelastic damping on dynamic behaviors of thermoelastic fields are studied in details. Also, the effects of different loading parameters on the thermoelastic damping are studied for various kinds of nano-beam resonators.

2. Governing equation

Nonlocal elasticity theory is briefly introduced in this section. In the theory of nonlocal elasticity [29], the stress at a reference point x is considered to be a function of the strain field at every point in the body. This observation is in accordance with atomic theory of lattice dynamics and experimental observation on phonon dispersion. When the effects of strains at points other than x are neglected, one obtains classical or local theory of elasticity.

The basic equations for linear, homogeneous, isotropic, non-local elastic solid with zero body force are given by [29,38]

$$\sigma_{kl,k}+\rho(f_l-\ddot{u}_l)=0 \tag{1}$$

$$\sigma_{kl}(x)=\int_v \alpha\left(|x'-x|\right)\tau_{kl}dV \tag{2}$$

$$\tau_{kl}=\lambda u_{n,n}\delta_{kl}+\mu(u_{k,l}+u_{l,k}) \tag{3}$$

where σ_{kl}, τ_{kl}, ρ, f_l and u_l are the non-local stress tensor, classical stress tensor, mass density, body force and displacement vector at a point $\boldsymbol{x}$ in the body, respectively. λ and μ are the Lame constants and V is the volume occupied by the elastic body. The non-local kernel $\alpha(|x'-x|)$ reflects the impact of the strain at the point x' on the stress at the point x. Note that the constitutive equation in the non-local continuum elasticity is expressed by an integral over the entire elastic body [31,33].

Beams with rectangular cross-section are mostly employed in NEMS resonators. A nano-resonator can be modeled as an elastic prism beam with either doubly clamped or simply supported ends. Here, it is considered small flexural deflections of a thin elastic beam with dimensions of length l, width b and thickness h. The x axis along the beam and the y and z axes correspond to the