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Surface and thermal effects of the flexural wave propagation of piezoelectric functionally graded nanobeam using nonlocal elasticity

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ABSTRACT

This study investigates the propagation peculiarities of the flexural wave of piezoelectric functionally graded nanobeam with surface and thermal effects. The equation of the flexural wave of the piezoelectric functionally graded nanobeam was expressed using nonlocal elastic theory because of the thermal and surface effects. The phase and group velocities were derived. The dispersion relation was analyzed using different wave numbers and temperatures and scale coefficient. The dispersion degree was weakened by scale coefficient and temperature and an increase in wave numbers. Changing the scale coefficient and temperatures are two of the main approaches in investigating the propagation characteristics of piezoelectric functionally graded nanobeam with surface effects and identifying new characteristics were found.

1. Introduction

Given the development of material technology and the superior properties of functionally graded materials (FGMs), these materials have received considerable attention and have been accorded with great practical importance because of their vast applications in the fields of industrial and engineering. Several studies have been conducted [1–9] using materials (FGMs) that have been widely employed in nano- and micro-structures, such as micro- and nanoelectromechanical systems [10–12], atomic force microscopes [13], and thin films in the form of shape memory alloys [14,15]. Research on functionally graded nanobeams has gained considerable theoretical significance and importance in engineering.

The classical continuum theory does not have a sufficient level of generality and fails to characterize the size effect of nanostructures by introducing an intrinsic length scale [10]. By contrast, the nonlocal continuum model developed by Eringen [16–19] has been widely and successfully applied in analyzing the size effect of nanostructures, as shown in several studies [20–24].

Classical continuum mechanics ignores the effect of surface energy because it is smaller than bulk energy. However, based on the surface stress [25–31], the size-dependent mechanical behavior of nanobeams has gained considerable attention. Moreover, surface effects are significant in nanoscale materials and structures because of their high surface/volume ratio, as shown in several studies [32–35] Li Yuhang did surface effects related research [36–38].

Studies have also focused on the problems of functionally graded nanobeams. Naotake Noda [39] investigated the thermal stresses in FGMs. Huang and Shen [40] studied the nonlinear vibration and dynamic response of functionally graded plates in thermal environments. H.S. Shen [41] presented the nonlinear bending response of functionally graded plates subjected to transverse loads under thermal environments. FGMs were subjected to thermal loading to produce large thermal stresses. Studying thermal stresses in FGMs with a variety of changes is significant.

The wave propagation characteristics of functionally graded nanobeams can be investigated by applying the classical Bernoulli–Euler and Timoshenko beam models. The equations of dispersion relation are accurately expressed for beam models and are presented for different materials. The angular frequency and the phase and group velocities in phenomenological size-dependent beam models increase with increased wave numbers. However, the velocity ratios of different materials approach different values. Moreover, few studies have examined the elastic wave propagation of FGMs.

Flexural vibration was studied [42]. However, the present study investigates the flexural wave in the piezoelectric functionally graded nanobeams with thermal and surface effects through nonlocal elastic theory. The results showed new and interesting phenomena. The surface and thermal effects of the flexural wave propagation of piezoelectric functionally graded nanobeams were considered in this model and presented in the numerical results.

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Nomenclature

EI	the equivalent flexural rigidity	T	temperature
e_0a	the scale coefficient	$\alpha(z)$	thermal expansion coefficient
v	Poisson's ratio	e_{31}	the piezoelectric coefficient
$\mu(z)$	the Lame constant	τ_{s1}	the top surface mass residual stress
$\rho(z)$	mass density	τ_{s2}	the bottom surface mass residual stress
ρ_{s1}	the top surface mass density	$\lambda(z)$	the Lame constant
ρ_{s2}	the bottom surface mass density	V	voltage

2. Equation of wave motion

The rectangular piezoelectric functionally graded nanobeam with a length of $L(0 \leqq x \leqq L)$, thickness of $2h(-h \leqq z \leqq h$, and width of b $(-0.5b \leqq y \leqq 0.5b)$, as illustrated in Fig. 1, was investigated. And the nonlocal governing equation of the piezoelectric FG nanobeam in the presence of the surface and thermal effects can be given by [43–50]:

$$\begin{cases} a_1 \frac{\partial^4 w}{\partial x^4} + a_2 \frac{\partial^4 w}{\partial x^2 \partial t^2} + a_3 \frac{\partial^2 w}{\partial t^2} - a_4 \frac{\partial^2 w}{\partial x^2} = 0 \\ a_1 = EI + (e_0 a)^2 F \\ a_2 = \frac{2\upsilon b h^2}{5} - (e_0 a)^2 a_3 \\ a_3 = b[\int_{-h}^{h} \rho(z) dz + (\rho_{s1} + \rho_{s2})] \\ a_4 = F \end{cases} \tag{1}$$

$$\begin{cases} F = F_1 + F_2 + F_3 \\ F_1 == 2Vbe_{31} \\ F_2 = (\tau_{s1} + \tau_{s2})b \\ F_3 = \int_{-h}^{h} \{3\lambda(z) + 2\mu(z)\}\alpha(z)Tdz \end{cases} \tag{2}$$

where F is the total equivalent transverse load, F_1 is the equivalent load due to the piezoelectric layer, F_2 is the an effective transverse distributed loading along the nanobeam longitudinal direction, because of surface effects, F_3 is the normal resultant forces due to the thermal loading [49,53], by integral, EI is got by stress strain σ_x [43,50]

$$\sigma_x = E(z)\varepsilon_x + \upsilon\sigma_z = e_{31}E_z - (3\lambda + 2\upsilon)\alpha\Delta T \tag{3}$$

This study assumes that only the lateral displacement exists in the nanobeams, which means that the y-directional displacement v is zero. The displacement is given by [51]

$$w = W \exp[i(mx - \omega t)], \quad v = 0 \tag{4}$$

where W is the amplitude of the displacement, m the wave number of the flexural wave, and $i^2 = -1\omega$ the circular frequency.

Substituting Eq. (3) into Eq. (1), we obtain

$$\omega = \sqrt{\frac{a_1 m^4 + a_4 m^2}{a_3 - a_2 m^2}} \tag{5}$$

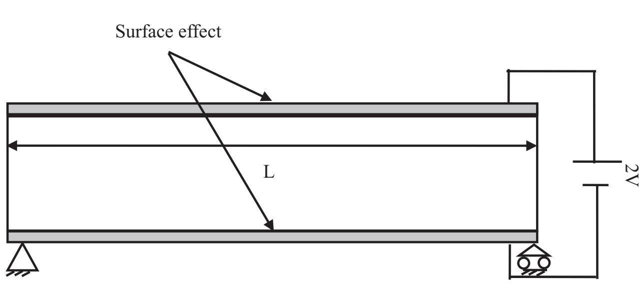

Fig. 1. A piezoelectric nanobeam with surface layer.

The expressions of the phase velocity $c_p = \omega/m$ and the group velocity $c_g = d\omega/dm$ can be written as

$$c_p = \sqrt{\frac{a_1 m^2 + a_4}{a_3 - a_2 m^2}} \tag{6}$$

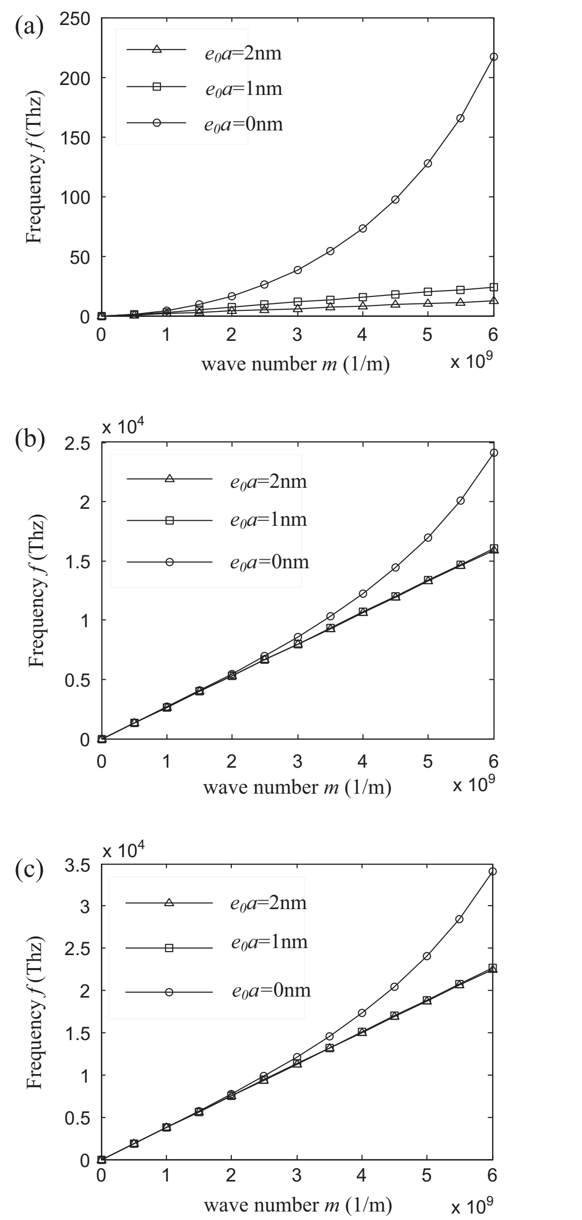

Fig. 2. (a) Under the conditions of T = 0 K, dispersion relation for nanobeams with different e_0a. (b) Under the conditions of T = 10 K, dispersion relation for nanobeams with different e_0a. (c) Under the conditions of T = 20 K, dispersion relation for nanobeams with different e_0a.