Ultrasonics 66 (2016) 65–71

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Propagation of Love waves with surface effects in an electrically-shorted piezoelectric nanofilm on a half-space elastic substrate

Sijia Zhang [a], Bin Gu [a,*], Hongbin Zhang [b], Xi-Qiao Feng [c], Rongying Pan [a], Alamusi [a], Ning Hu [d]

[a] School of Manufacturing Science and Engineering, Southwest University of Science and Technology, PR China
[b] School of Civil Engineering and Architecture, Hainan University, PR China
[c] Institute of Biomechanics and Medical Engineering, Department of Engineering Mechanics, Tsinghua University, PR China
[d] College of Aerospace Engineering, Chongqing University, Chongqing, PR China

ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form 4 November 2015
Accepted 5 November 2015
Available online 26 November 2015

Keywords:
Surface effects
Piezoelectric nanofilm
Electrically-shorted
Love wave
Frequency dispersion

ABSTRACT

The propagation of Love waves in the structure consisting of a nanosized piezoelectric film and a semi-infinite elastic substrate is investigated in the present paper with the consideration of surface effects. In our analysis, surface effects are taken into account in terms of the surface elasticity theory and the electrically-shorted conditions are adopted on the free surface of the piezoelectric film and the interface between the film and the substrate. This work focuses on the new features in the dispersion relations of different modes due to surface effects. It is found that with the existence of surface effects, the frequency dispersion of Love waves shows the distinct dependence on the thickness and the surface constants when the film thickness reduces to nanometers. In general, phase velocities of all dispersion modes increase with the decrease of the film thickness and the increase of the surface constants. However, surface effects play different functions in the frequency dispersions of different modes, especially for the first mode dispersion. Moreover, different forms of Love waves are observed in the first mode dispersion, depending on the presence of the surface effects on the surface and the interface.

1. Introduction

Taking advantages of the electro-mechanical coupling effects, piezoelectric nanoelements, such as piezoelectric nanowires and nanofilms, have been widely used in NEMS (Nano-Electro-Mechanical Systems) as nanoresonators, nanotransducer and nanoactuators. These piezoelectric devices possess great potentials in a wide range of applications where characteristic structural responses are usually utilized when dynamic loads, vibration and elastic waves in general, are applied [1–4]. For instance, based on the analysis on the shift of resonance frequency, Asemi et al. [4] used AlN piezoelectric nanofilms as nanoresonator and realized the nanoscale mass detection. It is well recognized that due to the extremely large ratio of surface area to volume, surface effects can have significant impact on material properties and behavior when the characteristic lengths of materials reduces to nanometers. Therefore, analysis on the vibration and wave propagation considering surface effects becomes crucial to proper designs of piezoelectric nanosensors. To incorporate surface effects in the framework of continuum mechanics, Gurtin and Murdoch [5] and Gurtin et al. [6] developed the surface elasticity theory for elastic solids which proved its feasibility by the direct atomistic simulations [7,8]. Coupling the piezoelectric effects, Pan et al. [9] extended the surface elasticity theory for piezoelectric materials in which surface electric displacements and the corresponding surface piezoelectric and dielectric constants are introduced. The surface elasticity theory assumes that a surface layer of zero thickness is perfectly adhered to the bulk material and the in-plane surface stresses, as well as the surface electric displacements for piezoelectric materials, exist in the surface layer. Moreover, it is hypothesized that surface stresses should include one part from the residual surface tension independent of the mechanical and electric fields of the bulk material, and another part from the surface elasticity which depends on the deformation and the electric intensity of the bulk material. Similarly, surface electric displacements are composed of two components from the residual surface electric displacement and the surface elasticity, respectively. So far, the surface elasticity theory has been widely adopted to investigate the mechanics properties and behaviors of nanostructured materials, as reviewed by Wang et al. [10].

* Corresponding author at: School of Manufacturing Science and Engineering, Southwest University of Science and Technology, Mianyang, Sichuan 621010, PR China.

E-mail address: gubin@swust.edu.cn (B. Gu).

http://dx.doi.org/10.1016/j.ultras.2015.11.009
0041-624X/

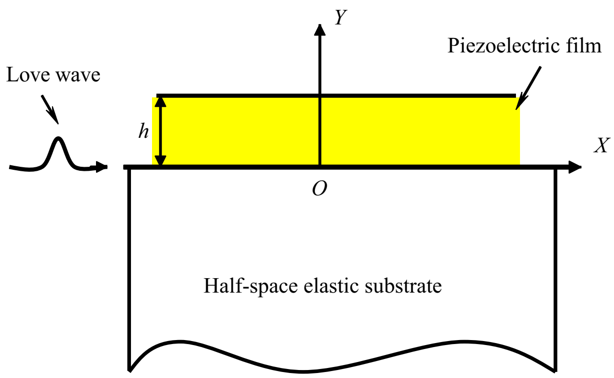

Fig. 1. Configuration of a piezoelectric film bonded with a semi-infinite elastic substrate.

As far as wave propagation problems are concerned, Wang and co-workers applied the surface elasticity theory to examine the surface effects on the propagation of plane waves diffracted by a single spherical or cylindrical nanoinclusion [11,12] and an array of nanosized cylindrical holes [13] in an infinite elastic medium. Fang et al. [14] studied the scattering of plane compressional waves by two interacting nanosized cylindrical inhomogeneities and discussed the effect of interfacial properties on dynamic stress concentration. Combining the surface elasticity theory with different approaches, surface effects on band structures of two dimensional phononic crystals with nanosized holes and inclusions are analyzed in the Refs. [15–17]. For piezoelectric nanomaterials, the surface effects on the diffraction of transverse shear waves by one nanofiber [18] and two interacting nanofibers [19] in piezoelectric matrices have been investigated. Analysis on the dispersion of plane compressional waves by a nanocylinder in an infinite piezoelectric medium is carried out by Zhang et al. [20]. In terms of the surface elasticity theory, Zhang and Chen [21] investigated the propagation of anti-plane shear waves in a piezoelectric nanoplate. Besides the surface elasticity theory, Chen [22] established a surface piezoelectricity theory based on a thin layer model and the state-space formalism. It is then applied to explore the impact of surface effects on the propagations of Bleustein–Gulyaev (B–G) wave in a piezoelectric half-space and transverse shear waves in a nanosized piezoelectric cylinder [23]. To date, research efforts on the elastic waves propagation in piezoelectric structures are still very limited once surface effects are considered.

As piezoelectric nanofilms which are nanosized in thickness and possess piezoelectric properties are often attached to a substrate of different physical properties in performances, surface effects on the propagation of elastic waves in the layered structures consisting of a piezoelectric nanofilm and a half-space elastic substrate are vital for the functions of piezoelectric nanofilms. Transverse shear waves in the above structures are referred as Love waves and have been extensively studied when surface effects are neglected [24–32]. To the author's knowledge, however, research on the Love waves propagation with surface effects has not yet reported in literature. By adopting the surface elasticity theory and the electrically-shorted conditions, dispersion of Love waves is investigated in this paper with the consideration of surface effects. This work aims to reveal the new features in the frequency dispersion of Love waves induced by surface effects. The effects of the film thickness and the surface constants are quantitatively examined for the dispersion relations of the first three modes.

2. Formulation of the problem

Consider a piezoelectric wave-guide structure in which a piezoelectric film of thickness h covers on a semi-infinite elastic substrate, as shown in Fig. 1. Referring to the Cartesian coordinate system (x, y, z), polarization direction of the piezoelectric film is aligned with the z direction and Love wave is incident along the x direction. The elastic substrate is homogeneous and isotropic. Surface effects exist on both the free surface of the piezoelectric film (denoted as the surface) and its interface with the substrate (denoted as the interface). Apparently, the surface effects on the surface and the interface are usually different because the atomic structures near the surface and the interface are not the same. Furthermore, the electric field of the piezoelectric film is assumed to be electrically-shorted, i.e., the electric potentials on the surface and the interface are zero.

According to the surface elasticity theory, surface effects only affect the boundary conditions of the bulk material on the surface/interface while the geometric equations, equilibrium equations and constitutive equations of the bulk materials keep the same as in the classical elasticity theory. For the problem of Love waves propagation, therefore, the displacement and the electric fields of the piezoelectric film and the elastic substrate have the following forms

$$\begin{aligned} &u_x = u_y = 0, \quad u_z = w(x,y,t), \quad \phi = \phi(x,y,t), \\ &u_x^{\mathrm{e}} = u_y^{\mathrm{e}} = 0, \quad u_z^{\mathrm{e}} = w^{\mathrm{e}}(x,y,t), \end{aligned} \tag{1}$$

where superscript "e" stands for the quantities related to the elastic substrate. $u_i (i = x, y, z)$ and ϕ are the displacements and the electric potential, respectively. Accordingly, the constitutive equations of the piezoelectric layer and the substrate can be deduced as

$$\sigma_{z\alpha} = c_{44} w_{,\alpha} + e_{15}\phi_{,\alpha}, \quad D_\alpha = e_{15} w_{,\alpha} - k_{11}\phi_{,\alpha}, \tag{2}$$

$$\sigma^{\mathrm{e}}_{z\alpha} = c^{\mathrm{e}}_{44} w^{\mathrm{e}}_{,\alpha}, \tag{3}$$

where $\sigma_{z\alpha}$ and $D_\alpha (\alpha = x, y)$ are the stresses and the electric displacements. c_{44}, e_{15} and k_{11} denote the elastic, the piezoelectric and the dielectric coefficients, respectively. Moreover, the equilibrium equations read

$$c_{44}\nabla^2 w + e_{15}\nabla^2\phi = \rho\frac{\partial^2 w}{\partial t^2}, \quad e_{15}\nabla^2 w = k_{11}\nabla^2\phi, \tag{4}$$

$$c^{\mathrm{e}}_{44}\nabla^2 w^{\mathrm{e}} = \rho^{\mathrm{e}}\frac{\partial^2 w^{\mathrm{e}}}{\partial t^2}, \tag{5}$$

where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ is the two-dimensional Laplace operator. ρ and ρ^{e} represent the mass densities of the piezoelectric film and the elastic substrate. The general solutions of Eqs. (4) and (5) can be written as

$$w(y) = (Ae^{k\lambda_1 y} + Be^{-k\lambda_1 y})e^{i(kx-\omega t)},$$

$$\phi(y) = \left[\frac{e_{15}}{\kappa_{11}}(Ae^{k\lambda_1 y} + Be^{-k\lambda_1 y}) + (Ce^{ky} + De^{-ky})\right]e^{i(kx-\omega t)}, \tag{6}$$

$$w^{\mathrm{e}}(y) = Ee^{k\lambda_2 y}e^{i(kx-\omega t)}, \tag{7}$$

where A, B, C, D and E are the unknown constants to be determined. k and ω are the wavenumber and the frequency. $\lambda_1 = \sqrt{1 - \frac{c_p^2}{c_F^2}}$ and $\lambda_2 = \sqrt{1 - \frac{c_p^2}{c_{\mathrm{HS}}^2}}$ with $c_p = \frac{\omega}{k}$, $c_F^2 = \frac{\bar{c}}{\rho}$, $\left(\bar{c} = c_{44} + \frac{e_{15}}{k_{11}}\right)$ and $c_{\mathrm{HS}}^2 = \frac{c^{\mathrm{e}}_{44}}{\rho^{\mathrm{e}}}$ being the phase velocity of Love waves, the velocities of the bulk transverse shear waves in the piezoelectric film and elastic half-space.

Boundary conditions on the surface and the interface are required to solve the unknown constants in (6) and (7). Due to surface effects, however, stresses and electric displacements are no longer continuous cross a surface/interface while the continuities of displacement and electric potential maintain. In terms of the sur-