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Size-dependent mechanical response of a nano-sized piezoelectric transducer with axially polarized multilayers

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HIGHLIGHTS

- The response of a piezoelectric nano-transducer under a voltage load is studied.
- Electro-elastic surface/interface model for axially polarized multilayers is given.
- The size-dependent behavior of cylindrical transducer is analyzed.
- The surfaces/interfaces effect on the mechanical response is discussed.

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ABSTRACT

Axially polarized piezoelectric fibers have been widely used in smart composites. This paper presents a theoretical investigation on the size-dependent mechanical response of a nano-sized piezoelectric cylindrical transducer with axially polarized multilayers subjected to an external harmonic voltage load. An electro-elastic surface/interface model is introduced to analyze the size-dependent stress in the transducer. Based on the plane stress assumption, the dynamic solution with surface/interface energy effect is expanded, and the expanded constants are solved by satisfying the boundary conditions at the surfaces/interfaces. An example is used to analyze the distribution of stress along the radial direction. It is found that the piezoelectric surfaces/interfaces in the nano-sized transducer exert greater effect on the mechanical response than the elastic surfaces/interfaces. The surfaces/interfaces effect on the inner layers is more evident than that on the outer layers. The surfaces/interfaces energy effect under different frequencies is also examined.

1. Introduction

Piezoelectric ceramic materials are finding increasing applications in piezoelectric devices such as ultrasonic transducers, sensors, actuators, generators, and transformers because of their ability of converting an electric stimulus into mechanical energy, and vice versa. These devices may be designed in many kinds of shapes such as stacks, beams, plates and cylinders. As one of the significant class of smart piezoelectric devices, the cylindrical transducers are attracting more and more interests [1,2].

Recent progress in manufacturing multilayered piezoelectric fibers with a transverse poling direction makes it possible to develop new smart composites, which can be used in different high frequency applications. These fibers have been widely used to design piezoelectric transducers and other smart multifunctional composite materials. Compared with the radius of the fibers, it is well known that the piezoelectric layer is relatively thin, and simplified layer models could be used to overcome this difficulty.

To increase the service performance and avoid the abrupt structural failures, it is requisite to investigate the electro-mechanical response of smart composites. It is generally thought that the characters of interfaces (interface stress and defects) around the fibers play an important role in improving the behavior of piezoelectric devices. Generally speaking, the interface strength is mainly responsible for the fatigue and degradation of piezoelectric transducers. The surface residual stresses in steel rods made of the same material but with different heat treatments have been studied by using the laser ultrasonic technique and piezoelectric transducers [3]. The initial stress effect on the propagation behavior of horizontally polarized shear waves (SH-waves) in a periodic multilayered piezoelectric composite structure was studied [4]. The fracture analysis was performed for a layered cylindrical piezoelectric sensor polarized along its axis, and the arc-shaped interface effect was discussed [5]. Based on the theory of plane stress

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and plane strain, the effects of an external shearing load on the properties of these two kinds of actuators are analyzed [6].

For nano-sized piezoelectric composites, an important issue is the high surface/interface ratio to the volume, and the interface energy will play a dominant role in controlling the response of piezoelectric devices. The dynamic property evolution of surface/interface in nanostructures was probed by Atomic Force Microscopy (AFM) [7]. The interface energy on the dynamic behavior of piezoelectric composites is attracting lots of interests in recent years [8]. Nowacki et al. presented the 2D electro-elastic fields in the piezoelectric layer-substrate structure with the general line defect, and the surface of the layer was supposed to be either metallized or adjoined to an isotropic dielectric medium. Chiu and Chen investigated the surface/interface stress effect on the bending behavior of piezoelectric nanowires based on the framework of linear membrane theory [9]. For a piezoelectric nano-particle in a polymer matrix under compressional waves, the surface/interface effect on the internal stress was analyzed, and the analytical solutions of stress and electric displacement were given [10]. An analytical solution was presented for the static deformation and steady-state vibration of simply supported hybrid cylindrical shells consisting of fiber-reinforced layers with embedded piezoelectric shear sensors and actuators [11].

With the wide application of axially polarized piezoelectric transducers in smart piezoelectric devices, the investigation on the dynamic behavior of axially polarized piezoelectric transducers is significant for the safe service. For the multilayered axially polarized piezoelectric transducers, the piezoelectric layers are generally anisotropic in the transverse direction, and the interface plays significant roles. Therefore, it is difficult to analyze the interface energy on the dynamic response when the dynamic loads are involved. Investigations on the dynamic analytical model of an axially polarized multilayer piezoelectric/elastic composite cylindrical transducer are very rare. In recent years, Wang and Shi studied the dynamic characteristics of an axially polarized multilayer piezoelectric/elastic cylindrical transducer, and the dynamic analytical solution under an external harmonic voltage load was obtained [12]. However, the surface/interface effect is ignored, which is a very important character for the smart piezoelectric composite cylindrical transducer.

In this paper, an improved surface/interface model is proposed to study the size-dependent dynamic behavior of an axially polarized multilayer piezoelectric cylindrical transducer subjected to an external harmonic voltage, and the interface energy effect resulting from the nano-sized property on the dynamic stress is analyzed. The plane stress assumption for the cylindrical transducer is introduced, and the dynamic analytical solutions of displacement and electric field are given. To analyze the interface energy effect on the dynamic response, the electro-mechanical surface/interface model is introduced. The numerical examples of stress in the transducer under different frequencies are presented and discussed.

2. Problem formulation

A nano-sized piezoelectric cylindrical transducer with axially polarized layers is considered, as shown in Fig. 1. The radius of the inner core is R_0. The elastic layers and piezoelectric layers are arranged alternately, and the numbers of elastic layers and piezoelectric layers are denoted by $n+1$ and n, respectively. It is assumed that the piezoelectric layers are polarized along the axial direction, and the axial thickness of the transducer is denoted by h.

The radial thicknesses of the mth elastic layer and the mth piezoelectric layer are determined by $(R_{2m-1}-R_{2m-2})$ and $(R_{2m}-R_{2m-1})$, respectively. The radial thicknesses of each layer may

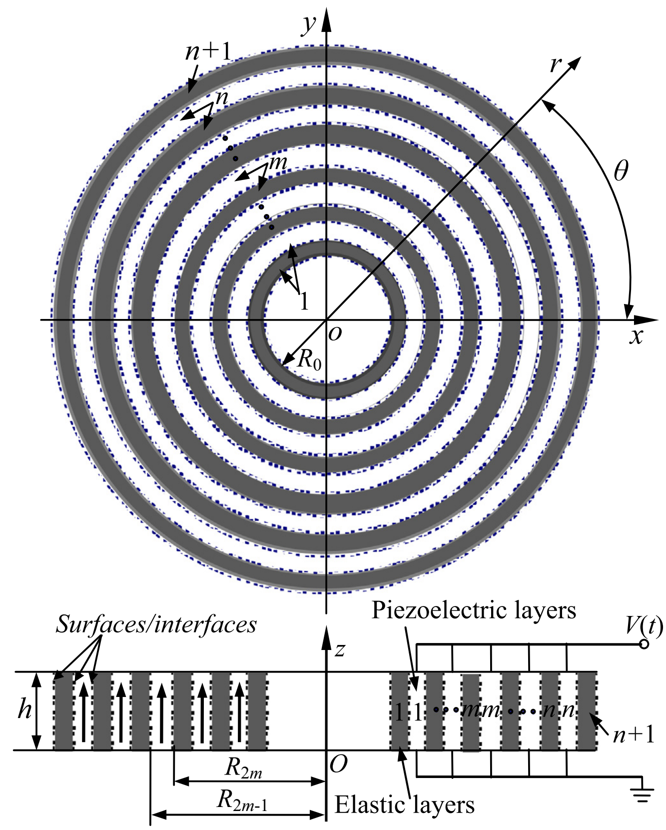

Fig. 1. A smart axially polarized piezoelectric transducer with piezoelectric/elastic layers and surfaces/interfaces.

be different. The transducer is excited by a harmonic external voltage $V(t)$ at the two sides of the transducer (see Fig. 1), and the excitation is expressed as

$$V(t) = V_0 e^{i\omega t}, \tag{1}$$

where V_0 is the amplitude of exciting voltage, $i=\sqrt{-1}$, ω is the circular frequency with $\omega = 2\pi f$, and t is time.

2.1. Basic solutions in the piezoelectric layers

For the mth piezoelectric layer, the dynamic governing equations of axisymmetrical radial vibration are expressed as

$$\frac{\partial \sigma_{rPm}}{\partial r} + \frac{\sigma_{rPm} - \sigma_{\theta Pm}}{r} = \rho_P \frac{\partial^2 u_{rPm}}{\partial t^2}, \tag{2}$$

$$\frac{\partial D_{zm}}{\partial z} = 0, \tag{3}$$

where σ_{rPm} and $\sigma_{\theta Pm}$ are the radial and tangential stresses in the mth piezoelectric layer, D_{zm} is the electric displacement, ρ_P and u_{rPm} are the density and the radial displacement, respectively. Note that the body force and body charge are neglected in this equation.

The linear constitutive equations for the mth piezoelectric layer under the plane stress can be expressed as

$$\sigma_{rPm} = c_{11}\varepsilon_{rPm} + c_{12}\varepsilon_{\theta Pm} - e_{31}E_{zm}, \tag{4}$$

$$\sigma_{\theta Pm} = c_{12}\varepsilon_{rPm} + c_{11}\varepsilon_{\theta Pm} - e_{31}E_{zm}, \tag{5}$$

$$D_{zm} = e_{31}\varepsilon_{rPm} + e_{31}\varepsilon_{\theta Pm} + \kappa_{33}E_{zm}, \tag{6}$$

where ε_{rPm}, $\varepsilon_{\theta Pm}$ represent the radial and tangential strains in the mth layer, E_{zm} is the axial electric field in the layer,