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Indentation response of piezoelectric films under frictional contact

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ABSTRACT

Piezoelectric materials are available in a variety of shapes and forms in smart systems. One of the most common shapes for sensor or actuator applications is the film form. To gain a better understanding of the indentation behavior of these systems, this work analyzes piezoelectric films under different 3D frictional contact boundary conditions. For this purpose, the boundary element formulation presented by authors in Rodríguez-Tembleque, Buroni, and Sáez (2015) is used for modeling piezoelectric finitely thick and thin films under orthotropic frictional indentation conditions, including tangential loads. The formulation has been applied to analyze the influence of friction and tangential loads on the electromechanical response of finitely thick piezoelectric films, ranging from a piezoelectric half space configuration, where the contact radius is much smaller than the thickness of the film, to a thin film configuration. Results reveal that these variables have to be considered to study the indentation response of these advanced systems. In other case, we could over- or underestimate the piezoelectric response and its distribution over the contact zone.

1. Introduction

Piezoelectric (PE) materials are highly demanded for numerous industrial and technological applications such as actuators, sensors or engineering control equipments among others. Because of the coupling effects between mechanical and electric fields, these materials present a great importance in the development of smart structures and systems (Ding & Chen, 2001; Ikeda, 1996; Yang, 2005). PE materials are available in a variety of shapes and forms in smart systems. One of the most common shapes for sensor or actuator applications is the film form (Mason, 1950; Muralt, 2008; Pohanka & Smith, 1988; Uchino, 1997), which has focussed the researchers attention for contact based energy harvesting and sensing applications during the last decades.

The films are usually bonded to substrate and their thickness is ranging from a few nanometers to several millimeters. Indentation techniques on thin-films and bulk forms have been studied theoretically and experimentally to have a better understanding of these piezoelectric systems under different contact conditions in order to measure their mechanical and electric properties. For instance, among these experimental works, references Fu, Ishikawa, Minakata, and Suzuki (2001); Kamble, Kubair, and Ramamurty (2009); Lefki and Dormans (1994); Ramamurty, Sridhar, Giannakopoulos, and Suresh (1999);

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Saigal, Giannakopoulos, Pettermann, and Suresh (1999) have instrumented indentation techniques to determine the piezoelectric properties of small systems and films.

Theoretical studies have also obtained the solution for piezoelectric half spaces and thin-films indentation. Many analytical and numerical works have focused on the indentation response of PE half-spaces i.e. Chen and Ding, 1999; Chen, Shioya, and Ding, 1999; Ding, Hou, and Guo, 2000; Fan, Sze, and Yang, 1996; Gao and Noda, 2004; Giannakopoulos and Suresh, 1999; Kalinin, Karapetian, and Kachanov, 2004; Ke, Yang, Kitipornchai, and Wang, 2008; Liu and Yang, 2012; 2013; Matysiak, 1985; Wang and Han, 2006; Wang, Fang, and Chen, 2002; Yang, 2008 . However, more recent works (Liu & Fuqian, 2012a; Wang & Chen, 2011; Wang, Chen, & Lu, 2008; Wu, Yu, & Chen, 2012) have considered piezoelectric films under frictionless normal indentation conditions. Wang et al. (2008) studied the axisymmetric indentation problem of a piezoelectric film perfectly bonded to a rigid substrate. Liu and Fuqian (2012a) analysed the spherical indentation of transversely isotropic piezoelectric films on rigid substrate, using the finite element method (FEM). The elastic substrate effect was studied by Wang and Chen (2011) and by Wu et al. (2012). Wang and Chen (2011) were concerned with the electromechanical indentation responses of the piezoelectric film perfectly bonded to an elastic substrate adopting frictionless contact condition between the indenter and the film and ideally bonding condition between the film and the substrate. Wu et al. (2012) considered the frictionless indentation of a piezoelectric film which either was in smooth contact with an elastic substrate, or was perfectly bonded to the elastic substrate.

To the best of authors' knowledge, the influence of (orthotropic) friction and tangential loads have not been included yet in the numerical studies on indentation response of piezoelectric films. So the present work analyzes the indentation response of general 3D geometries under piezoelectric contact including friction and tangential loads. To this end, the boundary element method (BEM) presented in Rodríguez-Tembleque, Buroni, and Sáez (2015) is used for modeling piezoelectric thin-films or bulk forms on a rigid substrate, in the presence of electric fields and orthotropic frictional contact conditions. The BEM is considered because its numerical suitability on 3D interface interaction problems where the number of degrees of freedom per node is increased due to the fact that the electric field is taken into account. The BEM considers only the boundary degrees of freedom, what makes possible to reduce the number of unknowns and to obtain a very good accuracy with less number of elements than finite element formulations (Barboteu, Fernández, & Ouafik, 2008; Han, Sofonea, & Kazmi, 2007; Hüeber, Matei, & Wohlmuth, 2013; Liu & Fuqian, 2012b). The proposed boundary element methodology is validated by comparison with analytical solutions presented by Wang et al. (2008) and then applied to study piezoelectric films under 3D frictional indentation.

The paper is organized as follows. First, a general formulation of the 3D piezoelectric contact problem is developed (i.e. governing equations and mechanical and electrical contact conditions). In Section 3, short description of the boundary element formulation and solution scheme is presented. Several numerical studies are presented in Section 4, where many different finitely thick films configurations are considered to study the influence of friction and tangential load on the electromechanical indentation response. Finally, the paper concludes with the summary and resulting conclusions.

2. Problem formulation

The indentation problem formulation of a 3D PE body $\Omega \subset \mathbb{R}^3$ with a boundary $\partial\Omega$, in a Cartesian coordinate system (x_i) $(i = 1, 2, 3)$, next described. The mechanical equilibrium equations of this problem, in the absence of body forces, and the electric equilibrium equations without the presence of free electrical charge are

$$\begin{aligned} \sigma_{ij,j} &= 0 \qquad \text{in} \quad \Omega, \\ D_{i,i} &= 0 \qquad \text{in} \quad \Omega, \end{aligned} \tag{1}$$

where σ_{ij} are the components of the Cauchy stress tensor and D_i are the electric displacements. The infinitesimal strain tensor γ_{ij} and the electric field E_i are defined as

$$\begin{aligned} \gamma_{ij} &= (u_{i,j} + u_{j,i})/2 \qquad \text{in} \quad \Omega, \\ E_i &= -\varphi_{,i} \qquad \text{in} \quad \Omega, \end{aligned} \tag{2}$$

with u_i being the elastic displacement and φ being the electric potential.

The elastic and electric fields are coupled through the linear constitutive law

$$\begin{aligned} \sigma_{ij} &= c_{ijkl}\gamma_{kl} - e_{lij}E_l \qquad \text{in} \quad \Omega, \\ D_i &= e_{ikl}\gamma_{kl} + \epsilon_{il}E_l \qquad \text{in} \quad \Omega, \end{aligned} \tag{3}$$

where c_{ijkl} and ϵ_{il} denote the components of the elastic stiffness tensor and the dielectric permittivity tensor, respectively; and e_{ijk} are the PE coupling coefficients. These tensors satisfy the following symmetries: $c_{ijkl} = c_{jikl} = c_{ijlk} = c_{klij}$, $e_{kij} = e_{kji}$, $\epsilon_{kl} = \epsilon_{lk}$, being the elastic constant and dielectric permittivity tensors positive definite.

Two partitions of the boundary $\partial\Omega$ are considered to define the mechanical and the electrical boundary conditions. The first one divides $\partial\Omega$ into three disjoint parts: $\partial\Omega = \partial\Omega_u \cup \partial\Omega_t \cup \partial\Omega_c$, being $\partial\Omega_u \cap \partial\Omega_t \cap \partial\Omega_c = \varnothing$. Here, $\partial\Omega_u$ denotes the boundary on which displacements $\tilde{u}_i$ are prescribed, $\partial\Omega_t$ denotes the part of the boundary where tractions $\tilde{t}_i = \sigma_{ij}\nu_j$ are imposed and $\partial\Omega_c$ represents the potential contact surface under rigid indentation, which have outward unit normal vector ν_{ci}. The second partition is: $\partial\Omega = \partial\Omega_\varphi \cup \partial\Omega_q \cup \partial\Omega_c$ $(\partial\Omega_\varphi \cap \partial\Omega_q \cap \partial\Omega_c = \varnothing)$, where the electric potential $\tilde{\varphi}$ is prescribed on $\partial\Omega_\varphi$ and the electric charge $\tilde{q} = D_i\nu_i$ is assumed on $\partial\Omega_q$. The formulation is general and makes it possible to consider