Ultrasonics 61 (2015) 145–150

Contents lists available at ScienceDirect

Ultrasonics

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

Effect of a functionally graded soft middle layer on Love waves propagating in layered piezoelectric systems

Issam Ben Salah [a,*], Morched Ben Amor [b,1], Mohamed Hédi Ben Ghozlen [a]

[a] Laboratory of Physics of Materials, Faculty of Sciences of Sfax, BP 1171, 3000 University of Sfax, Tunisia
[b] Sfax Preparatory Engineering Institute, Menzel Chaker Road 0.5 km, BP 1172, 3000 Sfax, Tunisia

ARTICLE INFO

Article history:
Received 24 December 2014
Received in revised form 23 April 2015
Accepted 24 April 2015
Available online 4 May 2015

Keywords:
Love waves
Soft middle layer
Functionally graded materials
Stiffness matrix method
ODE method

ABSTRACT

Numerical examples for wave propagation in a three-layer structure have been investigated for both electrically open and shorted cases. The first order differential equations are solved by both methods ODE and Stiffness matrix. The solutions are used to study the effects of thickness and gradient coefficient of soft middle layer on the phase velocity and on the electromechanical coupling factor. We demonstrate that the electromechanical coupling factor is substantially increased when the equivalent thickness is in the order of the wavelength. The effects of gradient coefficients are plotted for the first mode when electrical and mechanical gradient variations are applied separately and altogether. The obtained deviations in comparison with the ungraded homogenous film are plotted with respect to the dimensionless wavenumber. The impact related to the gradient coefficient of the soft middle layer, on the mechanical displacement and the Poynting vector, is carried out. The numericals results are illustrated by a set of appropriate curves related to various profiles. The obtained results set guidelines not only for the design of high-performance surface acoustic wave (SAW) devices, but also for the measurement of material properties in a functionally graded piezoelectric layered system using Love waves.

1. Introduction

Since the invention of interdigital transducers (IDT) (such as filters, delay lines, oscillators, and amplifiers), several applications have emerged in the area of signal processing, and information storage [1,2]. Such devices were successfully utilized for transmitting and receiving surface acoustic waves SAW (such as Love wave). Love wave sensors are highly sensitive devices owing to the concentration of acoustic energy within a few wavelengths of the surface. For this purpose layered piezoelectric structures consisting of a piezoelectric top layer and an elastic substrate or an elastic layer coupled to a piezoelectric substrate have been adopted [3,4,6]. Additionally the manufacture of such high performance devices, layered structures involving functional materials are also considered.

The propagation of Love wave in elastic or piezoelectric materials has been investigated by many researchers [3–6]. Li et al. [7] delivered his idea on the propagation of Love waves in functionally graded piezoelectric materials. Du et al. [8] investigated Propagation of Love waves in pre-stressed piezoelectric layered structures loaded with viscous liquid. Cao et al. [9] studied propagation of Love waves in a functionally graded piezoelectric material (FGPM) layered composite system. Furthermore, Liu et al. [10] investigated the Love waves in a smart functionally graded piezoelectric composite structure in which an FGPM layer is placed between a pure piezoelectric material layer and a metal substrate.

Accordingly the propagation of Love waves in structures having bonding between top layer and substrate has become a research topic of great interest, with a particular focus on the effects related to the bonded interface as well as the utilized glue [11,12]. The effect of an imperfect interface on the SH wave propagating in a cylindrical piezoelectric sensor has been discussed by Li and Lee [13]. In the same context the effects of a soft middle layer on Love waves propagating in layered piezoelectric systems have been recently reported [14].

In practice and mainly in SAW devices, due to various causes such as micro-defects, damage, the glue applied to dissimilar materials may weaken the interfacial continuity and further affect the performance of the heterogeneous structure. An adequate description of such additional soft middle layer is useful and its effect cannot be neglected even if the middle layer is typically thin, usually several micro-meters thick.

* Corresponding author. Fax: +216 74403934.
E-mail address: bs_issam@yahoo.fr (I. Ben Salah).
[1] Tel.: +216 74 241 403; fax: +216 74 246 347.

http://dx.doi.org/10.1016/j.ultras.2015.04.011
0041-624X/

The present work is motivated by recent contributions dealing with the effects of the elastic soft middle layer on wave propagation in layered piezoelectric structures by using a numerical approach [3,6,15–18]. Conversely to previous investigations mainly based on analytical methods [14,19], the numerical matrix method brings more flexibility, the gradient coefficient associated to electrical and mechanical properties of middle layer are assumed different. However when the propagating waves have more than one polarization, the analytical method seems unsuitable and no more solution can be extracted.

In the present study, a three-layer structure model is proposed for investigating the effect of a soft middle layer on Love waves propagating in layered piezoelectric systems. The soft character implies that the shear wave velocity (V_{SH} = 1041.51 m/s) of the middle layer is distinctly smaller than that of the upper piezoelectric layer (V_{SH} = 1751.11 m/s). In Section 2 we describe a three-layer composite structure and the developed numerical methods (Stiffness matrix method (SMM), as well as the ODE approach) [15–18]. Since the soft middle layer physical properties are dependent on depth, the layer is stratified and a computationally stable recursive method for wave propagation is applied. An illustrative example is considered, it includes a piezoelectric layer (PZT-5H) deposited on an elastic substrate (SiO_2) the same as [6]. This step is used to validate the developed codes under Matlab software. In Section 3 the description of dispersive behaviour is obtained under electrically open and short conditions. Additionally the effects of the middle layer thickness on phase velocity and electromechanical coupling factor are discussed. In the same way other aspects related to the Poynting vector and mechanical distributions are considered to bring more light on the system behaviour.

2. Theoretical background

2.1. System description

Consider wave propagation in a three-layer composite structure consisting of a transversely piezoelectric layer, a soft elastic middle layer and a half-space elastic substrate, as shown schematically in Fig. 1. For illustration a semi-infinite SiO_2 substrate carrying a polythene layer in the middle and a piezoelectric layer PZT-5H on the top assumed hexagonal, has been adopted.

The elastic and piezoelectric constants as well as the density and the dielectric constants, are reported in Table 1 [20].

Rectangular Cartesian coordinates (x_1,x_2,x_3) are selected such that the x_2-axis coincides with the polarization of Love wave. The Love mode becomes piezoactive with a high conversion rate, when the piezoelectric axis lies parallel to x_2 axis. h_f and h_s are the thickness of the top piezoelectric layer and the soft elastic middle layer, respectively.

2.2. Governing differential equations

Let us consider a three layer composite structure (Fig. 1) and a harmonic plane wave propagating along the x_1-axis of the form $\xi(x_3)\exp[i(k_1x_1 - \omega t)]$; where k_1 is the projection of the wave vector along x_1 the guiding direction.

The approach in this paper consists to have a first-order equation, which permits to use linear systems concepts and the well-known properties of first-order ODE's "Ordinary differential equation" and to satisfy interfacial boundary conditions in an extremely simple way [16–18]. The general solution for the state vector can be represented in this form as:

$$\xi(x_1, x_3, t) = \xi(x_3)\exp[i(k_1x_1 - \omega t)] \tag{1}$$

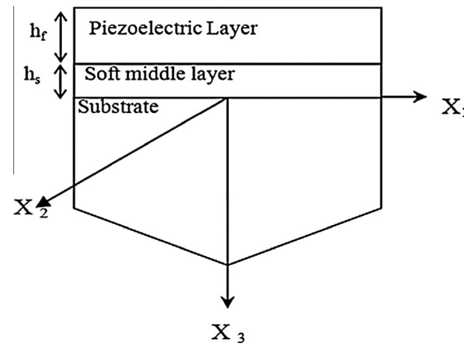

Fig. 1. A schematic configuration of a three-layer composite structure and coordinate system.

The normal stress vector $t_{i3} = [t_{13}, t_{23}, t_{33}]$ and the particle displacement $u = [u_1, u_2, u_3]$ are chosen as the six mechanical variables. For piezoelectric material the electric potential ϕ and the normal electric displacement component D_3, are chosen as two electric variables which must satisfy boundary relationships. This set of independent parameters is sufficient to describe the behaviour of any piezoelectric system. The eight-component state vector $\xi = [u\ \phi\ t_{i3}\ D_3]^T$ for the piezoelectric material and soft middle layer, is utilized to write suitable constitutive equations of the whole system in the form of an ordinary differential equation system in x_3 [16–18] :

$$\frac{\partial \xi}{\partial x_3} = iA\xi \tag{2}$$

where A is the fundamental acoustic tensor [16–18].

2.3. Implementation for a graded soft middle layer

We here assume that all material properties of the soft middle layer have the same profile along the x_3-axis direction with the following linear distribution: $\Gamma = \Gamma^0(1 + \alpha x_3)$, where α is the graded coefficient characterizing the degree of the material gradient in the x_3 direction and the superscript "0" is attached to indicate the value of the property Γ in the neighbourhood of $x_3 = 0$. Γ stands for any property among $\{C_{ijkl}, e_{ijk}, \varepsilon_{ik}, \rho\}$, these elements represent the elastic, piezoelectric, dielectric constants and the density, respectively. The superscript "0" denotes the property for the homogeneous material.

But it must be reminded that the electrical and mechanical parameters may be assigned differently in magnitude. Though these material constants distributions are unrealistic, it would allow us to understand the influence of soft middle layer gradient upon the characteristics of wave propagation, and make use of it for designing more effective devices in practice.

2.4. The boundary conditions

To describe the Love waves in a three layer composite structure, the following boundary and continuous conditions should be satisfied. It should be pointed out that two kinds of electrical boundary conditions, electrically open and shorted conditions, would be taken into account in this study.

As an example of electric boundary conditions, we consider either a shorted case (metalized) when potential is zero ($\phi = 0$) or a free surface (non-metalized) when the charge density is zero ($\sigma = 0$). The mechanical boundary condition for the external surface ($x_3 = -h$) is usually the stress-free condition ($t_{23} = 0$) with $h = h_s + h_f$.