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Lamb wave characteristics of thickness-graded piezoelectric IDT

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Abstract

An equivalent single layer model of Lamb wave generation by thickness-graded piezoelectric IDT on host structure is developed. Various additional complexities, such as the coupling between the Lamb wave modes, complicated nature of the electro-mechanical excitation are considered. The model of infinite IDT is extended to deal with the finite IDT with edge discontinuities. The effects of electromechanical coupling and thickness gradation on the wavelength shifts are investigated. The problem of electrically driven instability within the IDT is analyzed. Numerical results are reported by considering Al_2O_3/PZT IDT as integral part of the host structure, which show that there are significant changes and improvements in the Lamb wave characteristics due to the graded configuration. Most important among these is the reduced dispersiveness of the Lamb wave modes, which is useful in launching a SAW that propagates with narrower pulse width and less attenuation.

Keywords: IDT; Lamb wave; FGPM; Dispersion; Stability

1. Introduction

Surface acoustic wave devices in various forms of interdigital transducers (IDT) [1] have revolutionized the wireless communication, non-destructive testing (NDT) and bio-medical engineering. The work of Lord Rayleigh in 1885 [2] on surface acoustic wave (SAW) named after him, then the discovery of quartz resonator in 1921 by Walter Cady [3] employing the piezoelectricity, and later the use of periodic structure of electrodes in 1966 by White and Voltmer [4] opened up the possibility of using IDT on single or multi-layer piezoelectric/piezomagnetic heterostructure for launching SAW into the host structure. This technology has now several important applications in Health Monitoring of critical engineering structures [5–7]. In most of the ultrasonic application of SAW device, the IDTs are generally made on a thin or thick ferroelectric film, which is then adhesively bonded on the host structure. This gives rise to (1) the residual stress during bonding process (2) the interface defects and the possibility of interface crack growth (3) severe stress jumps across the interface during high electrical actuation or mechanical loading. As a result, one has to consider the operational limitations and life of the device for a particular application. A significant improvement in this context is possible by using functionally graded piezoelectric material (FGPM) patch as integral part of the host structure, where the electrodes of desired geometry can be deposited on the surface. An example is the PZT graded into Alumina or alloy. The main advantages here are the high toughness and good machinability of alloy and the high strength, high stiffness and high temperature resistance of ceramics, and better structural integrity of the FGPM based device. The graded composition leads to relaxation of stress at the interface between the device and the host structure. Zhu and Meng [8] and Wu et al. [9] have reported the development of FGPM actuators with

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gradation of compositions from high to low piezoelectric property and low to high dielectric property. However, use of such FGPM for Lamb wave device application is not well known. As a first step toward understanding whether the FGPM will improve the device performance, it is necessary to study the wave dispersion characteristics.

The characteristics of the launched SAW using a film on a substrate is well understood from the numerical solution to the Rayleigh wave propagation (surface wave in half space) and the Lamb wave propagation (Rayleigh wave in doubly bounded space) in isotropic material. Such analysis involving the additional pseudo-surface acoustic wave (PSAW), the Leaky Lamb wave in thickness-graded anisotropic composite structures is not well documented. Traditionally, the IDT configurations have been designed using the analysis as described by Milsom et al. [10]. Here the modeling assumptions are such that they do not couple the mechanics of the piezoelectric layer and the electrodes with the host structure. From the point of view of the interface electronics, the IDT structure can be modeled and analyzed using the equivalent electrical circuit approach as reported by Smith [11,12]. In order to extend the circuit model to the problem of the IDT operating on a thickness-graded composite host structures, one may need appropriate coupling between the device and the host structure, and hence need an array of resistors, capacitors and springs which would idealize the semi-conductive and finite thickness of the FGPM system. However, various issues related to numerical modeling are not well addressed. Wang and Varadan [13] reported an analytical model of shear horizontal (SH) SAW generation by IDT in bi-isotropic elastic half space by satisfying the interface tractions and displacement continuities at the film-substrate interface. This approach also applies to anisotropic piezoelectric layer on an anisotropic half-space, where the motion of a particle in and out of the *sagittal plane* can be considered in a coupled manner. However, using the layer-wise approach, the analysis of wave dispersion, the numerical simulation of the SAW generation and then propagation of the symmetric (S) and anti-symmetric (A) Lamb wave modes remain computationally very intensive. Also, the scattering of SAW from the interface of finite IDT and the host structure is an important factor in precision applications. For example, in structural health monitoring, the objective is to characterize small hidden defects or progressive damage. Canha and Adler [14] studied the problem of SAW scattering within IDT using the Method of Mode Matching (MMM). Although equally intensive, there exist alternatives to the layer-wise analytical model and MMM mentioned above. One of these alternative approaches is the detail finite element (FE) analysis reported by Hasegawa and Koshiba [15] and Xu [16]. However, the numerical analysis of wave dispersion over various frequency bands, which is essential to achieve the best design, is difficult while using the standard *hp* version of FE method.

From the above discussion, it is clear that efficient numerical analysis, understanding of the Lamb wave characteristics and subsequent design of FGPM-IDTs as integral part of the host structure are required. This can be achieved if the characteristic dispersion of the guided waves including the effect of electrical source term in IDT and the constitutive model of piezoelectricity are incorporated in a frequency domain FE model. A dynamic stiffness model of piezoelectric micro-strip array and numerical simulations was reported by Liu et al. [17]. However, only the S_0, A_0 and A_1 modes were targeted for minimally non-dispersive propagations. A coupled analysis based on spectral element method is reported in the present paper. The effect of FGPM-IDT geometrical parameters and finite space–time window are taken into account. The deformation in the thickness-graded region is modeled using higher-order shear deformation theory (HSDT). In such a model, the interface traction boundary conditions are satisfied accurately and the additional S_1 and A_2 Lamb wave modes are automatically included along with S_0, A_0, A_1 modes.

2. Waveguide model

We assume displacement field (u, w) in the thickness coordinate (z) of the thickness-graded piezoelectric structure (shown in Fig. 1(a)) based on the higher-order shear deformation as the guided waves propagate in x

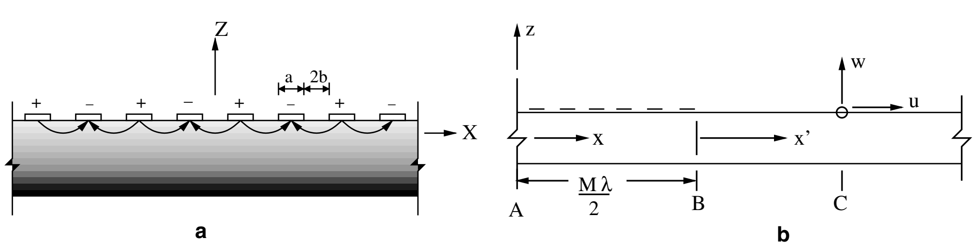

Fig. 1. (a) Thickness-graded piezoelectric structure and the surface electrode array showing the approximate distribution of the electric field. (b) Schematic diagram of the FGPM IDT and the host structure.