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Influences of mechanically and dielectrically imperfect interfaces on the reflection and transmission waves between two piezoelectric half spaces

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ABSTRACT

The influences of mechanically and dielectrically imperfect interfaces on the reflection and transmission waves between two piezoelectric half spaces are studied in this paper. First, the secular equations in the traverse isotropic piezoelectric half space are derived from the general dynamic equation. Then, six kinds of imperfect interfaces are considered. These imperfect interfaces include: the mechanically compliant, dielectrically weakly conducting imperfect interface; the mechanically compliant, dielectrically highly conducting imperfect interface; the grounded metallized interface and the low-dielectric interface and their mechanical counterpart, namely, the fixed interface and the slippery interface. These imperfect interface conditions are required to be satisfied by four sets of waves, namely, the quasi-longitudinal wave (QP), the quasi-transverse wave (QSV), the shear horizontal wave (SH) which is decoupled to other waves and the electric-acoustic wave (EA). The algebraic equations resulting from the imperfect interface conditions are solved to obtain the amplitude ratio of various waves and furthermore the reflection and transmission coefficients in terms of the energy flux ratio. The numerical results are obtained for the incident QP wave, the incident QSV wave and the incident SH wave and are validated by the energy conservation principle. The effects of these imperfect interfaces are discussed based on the numerical results. The present study provides useful information for the detection of imperfect interface.

1. Introduction

During the past few decades, the wave propagation in piezoelectric materials has evolved into a significant research due to its unique electromechanical coupling effect. Alshits and Shuvalov (1995) considered a shear horizontal elastic wave inclined incidence on a periodic structure of piezoelectric layers. It was shown that the reflection spectrum exhibited some specific features such as high selectivity, modulation of the heights of the Bragg maximums, and the extinction effect. Jin et al. (2002) studied the Lamb wave propagation in a metallic semi-infinite medium covered with a piezoelectric layer. It was shown that the phase speeds of Lamb wave are asymptotic to the transverse velocity of the piezoelectric layer as the wavenumber increases. Li and Wang (2006) studied disordered and ordered periodic layered piezoelectric composite structures. The phenomenon of wave localization in disordered periodic structures and the properties of frequency passbands and stopbands in ordered periodic structures were observed. Pang et al. (2008) investigated the reflection and refraction of QP and QSV waves incidence obliquely at the interface between piezoelectric and piezomagnetic media. The reflection or transmission waves in the incident plane consist of four kinds of waves. There are the electroacoustic wave (EA) and the magnetic potential wave (MP) in the piezoelectric medium and the magnetoacoustic wave (MA) and the electric potential wave (EP) in the piezomagnetic medium, besides the coupled QP and QSV waves. Rodríguez-Ramos et al. (2011) investigated the behavior of SH wave propagation with oblique incidence in piezocomposite layered systems. The transmission coefficients with respect to the frequency, incidence angle and piezoelectric volume fraction were studied. Singh (2013) studied the reflection and transmission of SH wave at elastic/piezoelectric and piezoelectric/piezoelectric interfaces. The amplitude and energy ratios against the incidence angle were obtained for the Steel/PZT4 and PZT4/PZT-5H interfaces. Lan and Wei (2014) studied the band gaps of laminated piezoelectric phononic crystal with graded interlayer. It was discussed the influences of the graded interlayer with different gradient profiles on the band gap of laminated piezoelectric phononic crystal. Apart from the bulk wave, the surface waves were also studied, for example, Li and Wei (2014) investigated

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the direction dependence of surface wave speed and the influence of electrically and magnetically short/open circuit conditions in the magneto-electro-elastic material. Four kinds of combinations of the short and open circuit conditions were taken into consideration. Because the reflection and transmission of elastic waves at boundary or interface of piezoelectric materials are fundamental for other further researches, it is interesting especially and thus attracted many researchers. Other references related to the reflection and transmission problem also includes Abd-alla and Alsheikh (2009), Abd-alla et al. (2012, 2014) and so on.

In all the aforementioned works, the interface between two different materials was treated as perfect bonded, namely, the displacement, the traction, the electric potential and the normal electric displacement were continuous across interface. In reality, the presence of interfacial defects due to the accumulative interfacial damages and local debonding is unavoidable. Therefore, the influences of imperfect interface with mechanical or dielectrical quantity jump across interface on the wave propagation are interesting. Alshits and Shuvalov (1993) analyzed Bragg resonance and the reflection of a transverse elastic wave from a periodic piezomagnetic structure with thin superconducting interlayers and also from a periodic piezoelectric structure with metallized interfaces. Fan et al. (2006) investigated certain waves which created the fluctuation perpendicular to incident plane and propagated near an imperfectly bonded interface between two half-spaces of different piezoelectric materials. The existence of these waves relies on the imperfection of the interface bonding. Wang and Sudak (2007) studied the influence of mechanically compliant and dielectrically weakly (or highly) conducting interface when presented the analytical solution of a piezoelectric screw dislocation located within one of two joined piezoelectric half-planes. Huang et al. (2009) studied the interfacial SH waves propagating along the imperfectly bonded interface of a magnetoelectric composite consisting of piezoelectric (PE) and piezomagnetic (PM) phases. It was shown that the interfacial imperfection strongly affects the velocity of interfacial shear waves and the interfacial shear waves do not exist for perfect interface. Lan and Wei (2012) studied the dispersive characteristics of elastic waves propagating through laminated piezoelectric phononic crystal with the mechanical imperfect interfaces. It was discussed the influences of the imperfect interface on the dispersive curves and the band gaps of periodic laminated piezoelectric composite. Piliposyan (2012) investigated the problem of the existence and propagation of a surface SH wave at the interface of two magneto-electro-elastic half-spaces. Four sets of boundary conditions, namely, full contact, partial contact with magnetically closed boundaries, partial contact with electrically closed boundaries and no electromagnetic contact, were considered. Pang and Liu (2011) investigated the reflection and transmission of plane waves at an interface between piezoelectric (PE) and piezomagnetic (PM) media. The mechanical imperfection of bonding behavior at the interface was described as the linear spring model. But the dielectrically imperfect interfaces were not considered. Moreover, the energy fluxes of various waves were not calculated and the numerical results were not validated by the energy flux conservation. Besides, the dependence of reflection and transmission coefficients on the apparent wavenumber in the case of imperfect interfaces was ignored too.

In this paper, the influences of six kinds of imperfect interfaces between two piezoelectric half spaces on the energy partition of reflection and transmission waves are firstly considered. Two of them, of most importance, are the mechanically compliant while dielectrically weakly conducting imperfect interface and the mechanically compliant while dielectrically highly conducting imperfect interface. Moreover, the grounded metallized interface and the low-dielectric interface, and their mechanical counterpart, namely, the fixed interface and the slippery interface, are also considered. These imperfect interface conditions result in a set of algebraic equations from them the reflection and transmission coefficients in terms of the displacement amplitude ratio can be obtained and furthermore the reflection and transmission coefficients in terms of the energy flux ratio are calculated. In present work, the reflection and transmission coefficients in terms of the energy flux ratio are provided instead of the displacement amplitude ratio as in most previous literatures because the energy flux ratio can be used directly to validate the numerical results whereas the displacement amplitude ratio cannot. The numerical calculations are performed for three kinds of incident waves, namely, QP wave, QSV wave and SH wave. The effects of these mechanically and dielectrically imperfect interfaces on the energy partition of reflection and transmission waves are discussed based on the numerical results.

2. Secular equation and vibration mode of coupled waves

Two piezoelectric half spaces which are transversely isotropic are imperfectly bonded at plane $x_3 = 0$ and their poling directions are parallel to the x_3 axis, see Fig. 1. The materials at both sides of interface are of different material constants. C_{ijmn}, e_{mij}, ε_{mi} and ρ are the elastic constants, piezoelectric constants, dielectric constants and mass density, respectively. The superscript R and T denote quantities relative to the reflection and transmission waves, respectively.

The constitutive equation of piezoelectric material is (Auld, 1990)

$$\begin{cases} \sigma_{ij} = C_{ijmn}S_{mn} - e_{mij}E_m \\ D_m = e_{mij}S_{ij} + \varepsilon_{mi}E_i \end{cases}, \tag{1}$$

where σ_{ij} and S_{mn} are the stress and strain tensor, respectively. E_m and D_m are the electric field and electric displacement vector, respectively. The strain tensor S_{mn} is related with the displacement vector u_n by

$$S_{mn} = \frac{1}{2}(u_{n,m} + u_{m,n}), \tag{2}$$

and the electric field vector E_m is related with the electric potential φ by

$$E_m = -\varphi_{,m}, \tag{3}$$

in the quasi static electric field approximation.

The mechanical and electrical governing equation can be expressed as

$$\begin{cases} \sigma_{ij,i} = \rho\ddot{u}_j \\ D_{m,m} = 0 \end{cases}. \tag{4}$$

In either plane strain or anti-plane strain case, the displacement field and the electric potential are only the function of x_1 and x_3

$$\begin{cases} \mathbf{u} = \{u_1(x_1,x_3,t), u_2(x_1,x_3,t), u_3(x_1,x_3,t)\} \\ \varphi = \varphi(x_1,x_3,t) \end{cases}, \tag{5}$$

and can be assumed as:

$$\{u_1,u_2,u_3,\varphi\} = \{U_1,U_2,U_3,\Phi\}\exp[i(k_1x_1 + k_3x_3 - \omega t)], \tag{6}$$

where the wavenumber $k = (k_1, k_2, k_3) = (k_1, 0, k_3)$ and k_1 is the apparent wavenumber.

Inserting Eqs. (6) and (1) into Eq. (4) leads to

$$\begin{bmatrix} T_{11} & 0 & T_{13} & T_{14} \\ 0 & T_{22} & 0 & 0 \\ T_{31} & 0 & T_{33} & T_{34} \\ T_{41} & 0 & T_{43} & T_{44} \end{bmatrix} \cdot \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \\ \Phi \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}. \tag{7}$$