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SH Waves in $(1-x)\mathrm{Pb}(\mathrm{Mg}_{1/3}\mathrm{Nb}_{2/3})\mathrm{O}_3$-$x\mathrm{PbTiO}_3$ Piezoelectric Layered Structures Loaded with Viscous Liquid**

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ABSTRACT The velocity dispersion and attenuation of shear horizontal (SH) waves in a layered piezoelectric structure loaded with viscous liquid is studied, where the $(1-x)\mathrm{Pb}(\mathrm{Mg}_{1/3}\mathrm{Nb}_{2/3})\mathrm{O}_3$-$x\mathrm{PbTiO}_3$ [PMN-xPT] single crystal is chosen as the piezoelectric layer. The PMN-xPT is being polarized along $[011]_c$ and $[001]_c$ so that the macroscopic symmetries are mm 2 and 4 mm, respectively. For the nonconductive liquid, the electrically open and shorted conditions at the interface between the liquid and the piezoelectric layer are considered. The phase velocity equations are derived analytically. The effects of the electrically boundary condition, the viscous coefficient and mass density of liquid as well as the thickness of the PMN-xPT layer on the phase velocity and attenuation are graphically illustrated. The results show that the phase velocity for the $[011]_c$ polarized PMN-0.29PT is much smaller than that for the $[001]_c$ polarized PMN-0.33PT, and the effects of viscous coefficient and piezoelectric layer thickness on the phase velocity for the $[011]_c$ case are stronger than that for the $[001]_c$ case. In addition, the electrical boundary conditions have an obvious influence on the propagation behaviors. These results can be useful for the designs and applications of acoustic wave devices and liquid biosensors.

KEY WORDS PMN-xPT single crystal, piezoelectric material, SH wave, viscous liquid, phase velocity, attenuation

I. Introduction

Surface acoustic wave (SAW) devices have recently become one of the most important applications in the electronic industry. In the fields of bio-sensing, chemical sensing and agricultural science, the development of acoustic waves has attracted much interest in the investigations of wave propagation in a layered piezoelectric medium loaded with viscous liquid[1–6]. Zhang et al.[7] proposed that the Bleustein-Gulyaev (B-G) wave was a promising candidate for liquid sensing applications. However, they did not give a detailed quantitative investigation of the characteristics of the B-G wave propagating in piezoelectric materials loaded with viscous liquid. Kielczyński et al.[8] presented a method for measuring the shear storage modulus and viscosity of liquids by using the B-G wave. Lee and Kuo[9] investigated the Lamb wave propagating in a piezoelectric plate subjected to conductive fluid loading. McMullan et al.[10] studied the Love wave in layered piezoelectric structures in various liquids. Wu and Chang[11]

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investigated the velocity dispersion and wave attenuation of layered or double-layered piezoelectric half-space structures loaded with viscous liquid. By using the transfer matrix method, Du et al.[12] studied the SH surface wave propagating in layered functionally graded piezoelectric structures loaded with viscous liquid. The effects of the graded parameter on the phase velocity and attenuation were also discussed. Furthermore, Du et al.[13] analyzed the effects of initial stress on the Love wave propagation properties in the piezoelectric layered structure loaded with viscous liquid. Guo and Sun[14] studied the B-G wave in 6 mm piezoelectric half-space loaded with viscous liquid and discussed the effects of viscosity and density of liquid on phase velocity and attenuation. Assuming the thickness of a liquid layer to be finite, Qian et al.[15] considered the problem similar to that in Ref.[14] and focused on the influence of thickness on the phase velocity of the B-G wave.

In the above-mentioned work, the quartz and piezoelectric ceramics were chosen as the piezoelectric materials. In order to improve the performance of piezoelectric devices for sensing applications, much effort has been done to develop new piezoelectric materials. In the past decade, it has shown that $(1-x)\mathrm{Pb}(\mathrm{Mg}_{1/3}\mathrm{Nb}_{2/3})\mathrm{O}_3$-$x\mathrm{PbTiO}_3$[PMN-$x$PT] single crystals are promise candidates for the applications in acoustic wave devices[16]. The PMN-xPT single crystal is ferroelectric with rhombohedral 3 m crystal symmetry at room temperature. However, its macroscopic symmetry depends on the polarizing direction because different polarizing directions will generate different domain patterns[17]. The macroscopic symmetry is tetragonal 4 mm for the $[001]_{\mathrm{c}}$ polarized sample[18], and orthogonal mm 2 for the $[011]_{\mathrm{c}}$ polarized sample[19]. The PMN-xPT single crystal poled in both $[001]_{\mathrm{c}}$ and $[011]_{\mathrm{c}}$ directions exhibits superior electromechanical properties at room temperature. Compared with the commonly used quartz or piezoceramics, the piezoelectric constants of PMN-xPT single crystals are 3-5 times larger. Recently, there is growing interest in PMN-xPT materials or structures. Chen and co-workers[20–22] investigated the propagation of guided waves in free standing PMN-xPT single crystal plates with different poled directions, where $x = 0.29$ and 0.33, respectively. They found that the coupling between the Lamb and SH modes existed for the $[111]_{\mathrm{c}}$ polarized direction[21], and revealed the crossing characteristics of lamb wave modes in $[001]_{\mathrm{c}}$ and $[011]_{\mathrm{c}}$ polarized directions. Li et al.[23–25] analyzed the propagation behaviors of surface acoustic waves in the semi-infinite PMN-xPT (PZN-xPT) single crystal in three kinds of polarized directions and showed the effects of cut orientations and polarizing directions on propagation velocity and electromechanical coupling coefficient. Based on the Love wave property, Huang et al.[26,27] proposed the high sensitivity gravimetric sensors made of carbon fiber epoxy composite layer perfectly and PMN-xPT single crystal substrate. Huang et al.[28] studied the Love wave propagation properties in a PMN-xPT substrate with a gold electrode film. However, to the authors' knowledge, the study of elastic wave propagating in PMN-xPT single crystal layered structure loaded with viscous liquid has not been done yet.

In this paper, we study the propagation of SH wave in a PMN-xPT piezoelectric layered structure loaded with viscous liquid. Two different polarizing directions of PMN-xPT are considered, i.e., $[011]_{\mathrm{c}}$ and $[001]_{\mathrm{c}}$. The dispersion relations for electrically shorted and open boundary conditions at the interface between the liquid and the piezoelectric layer are obtained analytically. In numerical examples, we discussed the effects of boundary condition, viscous coefficient and mass density of the liquid, as well as thickness of PMN-xPT on phase velocity and attenuation.

II. Problem Formulation

A layered piezoelectric structure loaded with viscous liquid is illustrated in Fig.1, where a half-space elastic substrate is covered by a PMN-xPT layer. The polarizing axis of piezoelectric material is placed in the x_3 direction. For a SH wave propagating in the x_1 direction, the components of displacement satisfy $u_1(x_1, x_2) = u_2(x_1, x_2)=0$, $u_3 = u_3(x_1, x_2, t)$, and the electric potential is $\varphi = \varphi(x_1, x_2, t)$. In this case, the constitutive relation for the $[011]_{\mathrm{c}}$ polarized PMN-xPT can be simplified into

$$\begin{Bmatrix} \sigma_{32} \\ \sigma_{31} \end{Bmatrix} = \begin{bmatrix} c_{44} & 0 \\ 0 & c_{55} \end{bmatrix} \begin{Bmatrix} u_{3,2} \\ u_{3,1} \end{Bmatrix} + \begin{bmatrix} 0 & e_{24} \\ e_{15} & 0 \end{bmatrix} \begin{Bmatrix} \varphi_{,1} \\ \varphi_{,2} \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} D_1 \\ D_2 \end{Bmatrix} = \begin{bmatrix} 0 & e_{15} \\ e_{24} & 0 \end{bmatrix} \begin{Bmatrix} u_{3,2} \\ u_{3,1} \end{Bmatrix} - \begin{bmatrix} \kappa_{11} & 0 \\ 0 & \kappa_{22} \end{bmatrix} \begin{Bmatrix} \varphi_{,1} \\ \varphi_{,2} \end{Bmatrix} \tag{2}$$

where σ_{31} and σ_{32} are the stress components, D_1 and D_2 are the electric displacement components, c_{44} and c_{55} are the elastic constants, e_{15} and e_{24} are the piezoelectric constants, and κ_{11} and κ_{22} are