SENRA Academic Publishers, British Columbia
Vol. 7, No. 3, pp. 2557-2570, October 2013
Online ISSN: 1920-3853; Print ISSN: 1715-9997

Canadian Journal of pure&applied sciences

NEW NONDISPERSIVE SH-SAWS GUIDED BY THE SURFACE OF PIEZOELECTROMAGNETICS

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ABSTRACT

This theoretical report provides the supplemental theoretical results concerning the propagation of the shear-horizontal surface acoustic waves in the transversely isotropic piezoelectromagnetics (magnetoelectroelastic materials) of class 6*mm*. In this theory, the pure SH-waves are guided by the free surface of the bulk piezoelectromagnetic material. The following mechanical, electrical, and magnetic boundary conditions at the common interface between two continua such as a vacuum and the bulk material are employed in this study: the mechanically free surface, continuity of both the electrical and magnetic inductions, and continuity of both the electrical and magnetic potentials. Based on the natural coupling mechanisms such as $e\alpha - h\varepsilon$ and $\varepsilon\mu - \alpha^2$ in the coefficient of the magnetoelectromechanical coupling (CMEMC) it is argued that some additional new true solutions for the new surface SH-waves can exist. The existing incorrect solutions for this problem are also given and discussed. The obtained theoretical results can be useful for constitution of various technical devices based on smart magnetoelectroelastic materials and the further researches on the propagation of the interfacial SH-waves and the plate SH-waves in the piezoelectromagnetic (composite) materials.
PACS: 51.40.+p, 62.65.+k, 68.35.Gy, 68.35.Iv, 68.60.Bs, 74.25.Ld, 74.25.Ha, 75.20.En, 75.80.+q, 81.70.Cv

Keywords: Piezoelectromagnetics, magnetoelectroelastic materials, magnetoelectric effect, new SH-SAWs.

INTRODUCTION

Piezoelectromagnetic materials, also known as the magnetoelectroelastic media, simultaneously show evidence of the piezoelectric, piezomagnetic, and magnetoelectric effects (Nan, 1994; Fiebig, 2005; Wang *et al*., 2007). The properties of such smart materials can offer multi-promising opportunities for the creation of intelligent structures and smart material technical devices. These innovative devices can be capable of responding to internal and environmental changes. Piezoelectromagnetic (PEM) shear-horizontal surface acoustic waves (SH-SAWs) can be very useful for analyzing high-frequency SH-SAW technical devices. PEM SH-SAWs can be readily generated with the well-known non-contact method (Ribichini, 2010; Thompson, 1990; Hirao and Ogi, 2003) called the electromagnetic acoustic transducers (EMATs). The utilization of this non-contact method can be preferable in comparison with the other traditional method based on the piezoelectric transduction (Thompson, 1990; Hirao and Ogi, 2003).

It is well-known that the magnetoelectric (ME) effect in the single phase PEM materials such as Cr_2O_3, $LiCoPO_4$, and $TbPO_4$ (Fiebig, 2005) is usually very small. Indeed, none of the magnetoelectric materials can have combined large and robust electric and magnetic polarizations at room temperature. However, the $Sr_3Co_2Fe_{24}O_{41}$ Z-type hexaferrite (Kimura, 2012) with a hexagonal structure was discovered in 2010. It is thought that such single-phase hexaferrite with the realizable ME effect can be already apt for practical applications. Also, two-phase PEM composite materials can be exploited in various technical devices. Composites possessing the ME effect consist of the piezoelectric and piezomagnetic phases. The ME coupling in such composites represents a product property resulting from the mechanical interaction between the piezoelectric and piezomagnetic phases. Experimental investigations of the ME effect in the two-phase composites were originated in the 1970s. In pioneer works Van Suchtelen (1972); Van den Boomgaard *et al*. (1974); Van Run *et al*. (1974); Van den Boomgaard *et al*. (1976), the piezoelectric phase $BaTiO_3$ and piezomagnetic phase $CoFe_2O_4$ materials were employed to synthesize the ME composite such as $BaTiO_3$-$CoFe_2O_4$ by a unidirectional solidification method. The resulting PEM $BaTiO_3$-$CoFe_2O_4$ composite can have two orders larger value of the ME coefficient than that of the pioneer single-phase ME crystal such as Cr_2O_3 (Liu *et al*., 2007). Annigeri *et al*. (2006) and Aboudi (2001) provide the material characteristics of various $BaTiO_3$-$CoFe_2O_4$ composites of hexagonal class 6 *mm*. These PEM composites relate to the (0-3) connectivity when the three-dimensional matrix of the piezoelectric phase contains zero-dimensional inclusions of the piezomagnetic phase, or vice versa. Also, PEM composites can have the (2-2) connectivity when a multi-layered (sandwich-like) structure is formed. Such PEM laminated composites can

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be composed of linear homogeneous piezoelectric and piezomagnetic layers with a perfect bonding between each interface. The investigations of such laminated composites are relatively recent (Ramirez *et al*., 2006) and the material parameters of the $BaTiO_3$–$CoFe_2O_4$ and PZT-5H–Terfenol-D laminated composites can be found in reported work (Wang and Mai, 2007; Liu and Chue, 2006; Zakharenko, 2012a; Wang *et al*., 2008). The PEM laminates can demonstrate significant interactions between the elastic, electric, and magnetic fields and have direct applications in sensing and actuating devices. There is indeed much review work (Fiebig, 2005; Kimura, 2012; Özgür *et al*., 2009; Fiebig *et al*., 2005; Park and Priya, 2012; Pullar, 2012; Bichurin *et al*., 2012; Zakharenko, 2013a; Chen *et al*., 2012; Bichurin *et al*., 2011; Srinivasan, 2010; Zhai *et al*., 2008; Nan *et al*., 2008; Eerenstein *et al*., 2006; Spaldin and Fiebig, 2005; Khomskii, 2006; Cheong and Mostovoy, 2007; Ramesh and Spaldin, 2007; Kimura, 2007; Kimura *et al*., 2003; Wang *et al*., 2009; Ramesh, 2009; Delaney *et al*., 2009; Gopinath *et al*., 2012; Fert, 2008a; Fert, 2008b; Chappert and Kim, 2008; Bibes and Barthélémy, 2008; Prellier *et al*., 2005; Bichurin *et al*., 2006; Fetisov *et al*., 2006; Srinivasan and Fetisov, 2006; Priya *et al*., 2007; Grossinger *et al*., 2008; Ahn *et al*., 2009; Petrov *et al*., 2003; Harshe *et al*., 1993; Chu *et al*., 2007; Schmid, 1994; Ryu *et al*., 2002; Fang *et al*., 2008; Sihvola, 2007; Hill, 2000; Smolenskii and Chupis, 1982) on the ME effect, PEM composites, and their applications.

It is thought that the first review work on the propagation of the PEM SH-SAWs guide by the free surface is paper Zakharenko (2013a). This paper partly reviews some achievements of the original theoretical work written by Melkumyan (2007) who has discovered several new SH-waves corresponding to different mechanical, electrical, and magnetic boundary conditions. Also, review paper Zakharenko (2013a) touches the problems of the PEM SH-SAW propagations in the transversely isotropic materials (Zakharenko, 2010) and the half-spaces with the cubic symmetry (Zakharenko, 2011a). It is necessary to state that following book Zakharenko (2010), the following section first acquaints the reader with recent theoretical achievements concerning the theory of SH-wave propagation guided by the free surface of the transversely isotropic piezoelectromagnetic half-space of class 6 *mm*. This theoretical work relates to the most complicated case of the electrical and magnetic boundary conditions at the vacuum-solid interface when the electrical and magnetic inductions and the electrical and magnetic potentials are continued through the interface. As a result, this work discusses the corresponding new SH-wave discovered in book Zakharenko (2010), discovers two additional new SH-waves for the case, and explains why the other existing solutions found in papers (Wang *et al*., 2007; Liu *et al*., 2007) cannot be true for the treated case of the boundary conditions mentioned above. Thus, the following section starts with the theory of the SH-wave propagation based on the book by Zakharenko (2010).

Theory of PEM SH-SAWs leading to some new solutions

For a PEM medium, acoustic wave propagation coupled with both the electrical and magnetic potentials requires suitable thermodynamic functions and thermodynamic variables. It is convenient to choose the mechanical stress, electrical induction (**D**), and magnetic induction (magnetic flux **B**) as the appropriate thermodynamic functions (Zakharenko, 2010; Zakharenko, 2011a; Zakharenko, 2012b; Zakharenko, 2012c). As a result, the thermodynamic variables for such choice are the mechanical strain, electrical field (**E**), and magnetic field (**H**). In such thermodynamic treatment in the case of linear elasticity, all the material constants can be thermodynamically determined. The components of the electrical field (E_i) and the components of the magnetic field (H_i) can be defined by the electrical potential φ and magnetic potential ψ, respectively: $E_i = -\,\partial\varphi/\partial x_i$ and $H_i = -\,\partial\psi/\partial x_i$, where x_i represent the real space components and the index i runs from 1 to 3. Utilization of the equilibrium equations and the corresponding Maxwell equations written in the form of the quasi-static approximation (Auld, 1990; Dieulesaint and Royer, 1980) can constitute the coupled equations of motion representing partial second derivatives. The solutions such as the mechanical displacement components U_i, electrical potential φ, and magnetic potential ψ for the coupled equations of motion can be naturally written in the form of plane waves.

Using the plane wave solution for the coupled equations of motion written in the differential form, it is possible to compose the coupled equations of motion written in the tensor form representing the well-known Green-Christoffel equation (Zakharenko, 2010; Zakharenko, 2011a; Zakharenko, 2012b; Zakharenko, 2012c). In the case of the linear elasticity, the modified Green-Christoffel tensor with the GL_{IJ}-tensor components is symmetric, i.e. $GL_{IJ} = GL_{JI}$, where the indices I and J run from 1 to 5. For that reason, it has only 15 independent tensor components. In the common case, the Green-Christoffel equation representing a polynomial can be resolved only numerically. The Green-Christoffel equation is the main equation to study acoustic wave propagation coupled with both the electrical and magnetic potentials. To resolve this equation means to determine the eigenvalues and corresponding eigenvectors, where the eigenvectors have the following common form consisting of five initial amplitudes:

$$\left(U_1^0, U_2^0, U_3^0, U_4^0 = \varphi^0, U_5^0 = \psi^0\right).$$

However there are high symmetry propagation directions (Dieulesaint and Royer, 1980; Lardat *et al*., 1971) in which "pure" waves with the in-lane polarization and "pure" waves with the anti-pale polarization (shear-horizontal polarization) can exist. The main feature of such pure waves mentioned in paper (Lardat *et al*., 1971) can be expanded for the case of the wave propagation in the piezoelectromagnetics: when the pure waves with the anti-plane polarization are coupled with both the electrical and magnetic potentials, the pure waves with the in-lane polarization represent purely mechanical waves, and vice versa. The suitable cuts and propagation directions for materials with various symmetry classes are tabulated in works (Dieulesaint and Royer, 1980; Lardat *et al*., 1971). It is central to state that each symmetry class has its own set of the material constants, for instance, see in books cited in Nye (1989), Newnham (2005), Lovett (1999), Hammond (2009) and Wooster (1973).

The theoretical work developed below relates to the study of propagation of shear-horizontal surface acoustic waves (SH-SAWs) in the transversely isotropic piezoelectromagnetic materials of symmetry class 6 *mm*. For materials of such symmetry, the suitable propagation directions are mentioned in review paper (Gulyaev, 1998) and the coordinate system is shown in review paper (Zakharenko, 2013a) available on-line with an open excess. Using the rectangular coordinate system (x_1,x_2,x_3), it is necessary to state that the SH-SAW propagation direction, sixfold symmetry axis of the PEM material, and the surface normal must be managed along the x_1-, x_2-, and x_3-axes, respectively. So, such propagation directions can support the coupling of the elastic SH-waves with both the electrical and magnetic potentials. For this case, the Green-Christoffel equation is simplified and all the eigenvalues and the corresponding eigenvectors such as $\left(U_2^0, U_4^0 = \varphi^0, U_5^0 = \psi^0\right)$ can be analytically found. In such propagation directions, different sets of the mechanical, electrical, and magnetic boundary conditions (Melkumyan, 2007; Zakharenko, 2010) can be treated. However, this work has the purpose to discover some additional new solutions (new SH-SAWs) only for the following set of the boundary conditions applied at the vacuum-solid interface: the mechanically free surface, continuity of both the electrical and magnetic inductions, and continuity of both the electrical and magnetic potentials. The various boundary conditions for the case when a medium simultaneously possesses both the piezoelectric and piezomagnetic properties are perfectly described in paper Al'shits *et al*. (1992). The following subsection provides the theory following book Zakharenko (2010). However, it is believed that the most comprehensive theory for the case is given in theoretical work (Zakharenko, 2012b) of books (Zakharenko, 2010; Zakharenko, 2011a; Zakharenko, 2012b; Zakharenko, 2012c).

Theory of SH-wave propagation, eigenvalues, and eigenvectors

In the suitable high symmetry propagation direction mentioned above when the SH-wave propagation is coupled with both the electrical and magnetic potentials there are the following independent nonzero material constants: the stiffness constant C, piezomagnetic coefficient h, piezoelectric constant e, dielectric permittivity coefficient ε, magnetic permeability coefficient μ, and electromagnetic constant α. These material constants are defined as follows: $C = C_{44} = C_{66}$, $e = e_{16} = e_{34}$, $h = h_{16} = h_{34}$, $\varepsilon = \varepsilon_{11} = \varepsilon_{33}$, $\mu = \mu_{11} = \mu_{33}$, and $\alpha = \alpha_{11} = \alpha_{33}$ (Zakharenko, 2010). The SH-SAWs are guided by the free surface of the transversely isotropic piezoelectromagnetics of class 6 *mm*. The anti-plane polarized SH-wave propagates along the x_1-axis of the rectangular coordinate system (x_1,x_2,x_3) and has the mechanical displacement component $U = U_2$ directed along the x_2-axis. The propagation direction can be defined by the directional cosines (n_1,n_2,n_3) respectively directed along the corresponding axes (x_1,x_2,x_3). For this case, the directional cosines are defined as follows: $n_1 = 1$, $n_2 = 0$, and $n_3 \equiv n_3$. They are coupled with the components (k_1,k_2,k_3) of the wavevector **K** by the following equality: $(k_1,k_2,k_3) = k(n_1,n_2,n_3)$ where k is the wavenumber in the propagation direction. All the suitable values of n_3 must be found and they represent the eigenvalues for the case. Using the found eigenvalues, the corresponding eigenvector $\left(U^0, \varphi^0, \psi^0\right) = \left(U_2^0, U_4^0, U_5^0\right)$ can be also determined from the corresponding tensor form of the coupled equations of motion.

When the SH-wave propagation is coupled with both the electrical potential φ and the magnetic potential ψ, the corresponding tensor form of the coupled equations of motion can be expressed by three homogeneous equations written in the following matrix form:

$$\begin{pmatrix} GL_{22} - \rho V_{ph}^2 & GL_{24} & GL_{25} \\ GL_{42} & GL_{44} & GL_{45} \\ GL_{52} & GL_{54} & GL_{55} \end{pmatrix} \begin{pmatrix} U^0 \\ \varphi^0 \\ \psi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad (1)$$

where ρ and V_{ph} are the mass density of the piezoelectromagnetic material and the phase velocity, respectively. The phase velocity V_{ph} is defined by the following relation: $V_{ph} = \omega/k$, where ω is the angular frequency.

All the suitable eigenvalues n_3 can be determined when the determinant of the coefficient matrix in equations (1) vanishes. Thus, it is possible to write the following matrix determinant:

$$\begin{vmatrix} GL_{22}-\rho V_{ph}^2 & GL_{24} & GL_{25} \\ GL_{42} & GL_{44} & GL_{45} \\ GL_{52} & GL_{54} & GL_{55} \end{vmatrix} = 0 \quad (2)$$

where the components of the symmetric *GL*-tensor are expressed as follows:

$$GL_{22} = C(1+n_3^2) \quad (3)$$

$$GL_{44} = -\varepsilon(1+n_3^2) \quad (4)$$

$$GL_{55} = -\mu(1+n_3^2) \quad (5)$$

$$GL_{24} = GL_{42} = e(1+n_3^2) \quad (6)$$

$$GL_{25} = GL_{52} = h(1+n_3^2) \quad (7)$$

$$GL_{45} = GL_{54} = -\alpha(1+n_3^2) \quad (8)$$

The matrix determinant written above can be rewritten in the following convenient form:

$$m \times m \times \begin{vmatrix} C\left[m-\left(V_{ph}/V_{t4}\right)^2\right] & em & hm \\ e & -\varepsilon & -\alpha \\ h & -\alpha & -\mu \end{vmatrix} = 0 \quad (9)$$

where $m = 1 + n_3^2$. In equation (9), V_{t4} stands for the speed of the shear-horizontal bulk acoustic wave (SH-BAW) uncoupled with both the electrical and magnetic potentials. This speed is defined by

$$V_{t4} = \sqrt{C/\rho} \quad (10)$$

It is clearly seen in equation (9) that the left-hand side consists of three factors, of which each provides its own eigenvalues. So, the first and second factors are the same and give the following identical eigenvalues:

$$n_3^{(1)} = n_3^{(3)} = -\mathrm{j} \quad (11)$$

where only eigenvalues with a negative imaginary part are left to have wave damping towards depth of the PEM material. So, the first and third eigenvalues defined by expression (11) are suitable because the second and fourth eigenvalues have an opposite sign.

Also, the third factor in equation (9) represents a determinant representing a number. The determinant must be equal to zero to reveal the third suitable eigenvalue n_3. Expanding this determinant, the following secular equation can be obtained:

$$\left(1+K_{em}^2\right)m - \left(V_{ph}/V_{t4}\right)^2 = 0 \quad (12)$$

In equation (12), K_{em}^2 stands for the coefficient of the magnetoelectromechanical coupling (CMEMC). It can be calculated with the following formula:

$$K_{em}^2 = \frac{\mu e^2 + \varepsilon h^2 - 2\alpha e h}{C\left(\varepsilon\mu - \alpha^2\right)} = \frac{e(e\mu - h\alpha) - h(e\alpha - h\varepsilon)}{C\left(\varepsilon\mu - \alpha^2\right)} \quad (13)$$

It is obvious in equation (13) that the CMEMC can be represented as the material parameter depending on the following three different coupling mechanisms (Zakharenko, 2013b):

$$e\mu - h\alpha \quad (14)$$

$$e\alpha - h\varepsilon \quad (15)$$

$$\varepsilon\mu - \alpha^2 \quad (16)$$

Consequently, equation (12) provides the following form of the third suitable eigenvalue denoted as the fifth eigenvalue:

$$n_3^{(5)} = -\mathrm{j}\sqrt{1-\left(V_{ph}/V_{tem}\right)^2} \quad (17)$$

because the sixth eigenvalue has an opposite sign and therefore, it is unsuitable for the case. So, the suitable three eigenvalues defined by expressions (11) and (17) are found. Using them, it is necessary to determine the corresponding eigenvectors. In definition (17), the velocity denoted by V_{tem} represents the speed of the SH-BAW coupled with both the electrical and magnetic potentials. It is defined by the following expression:

$$V_{tem} = V_{t4}\left(1+K_{em}^2\right)^{1/2} \quad (18)$$

Using equations (1), it is also possible to determine the eigenvector explicit forms such as $\left(U^0, \varphi^0, \psi^0\right)$ for all three suitable eigenvalues n_3 defined by expressions (11) and (17). It is natural to use the first equation in equations' set (1) to demonstrate the dependence of the eigenvector component U^0 on both the components φ^0 and ψ^0. Thus, one has

$$U^0 = -\frac{em}{A}\varphi^0 - \frac{hm}{A}\psi^0 \quad (20)$$

Next, dependence (20) is utilized in the second and third equations in equations' set (1) to exclude the eigenvector component U^0 and to deal with only two equations in two unknowns such as φ^0 and ψ^0. So, these two equations read:

$$\left(\frac{me^2}{A}+\varepsilon\right)\varphi^0+\left(\frac{meh}{A}+\alpha\right)\psi^0=0 \quad (21)$$

$$\left(\frac{meh}{A}+\alpha\right)\varphi^0+\left(\frac{mh^2}{A}+\mu\right)\psi^0=0 \quad (22)$$

where

$$A=C\left[m-\left(V_{ph}/V_{t4}\right)^2\right] \quad (23)$$

It is worth noting that the used mathematical procedure to obtain the eigenvector components such as U^0, φ^0, and ψ^0 is usual and well-known. Accounting the fact that $m = 1 + n_3^2 = 0$ for two eigenvalues (11), it is possible to have the following eigenvector components:

$$\left(U^{0(1)},\varphi^{0(1)},\psi^{0(1)}\right)=\left(U^{0(3)},\varphi^{0(3)},\psi^{0(3)}\right)=\left(0,\alpha,-\varepsilon\right) \quad (24)$$

For eigenvalue (17) with $m \neq 0$, the corresponding eigenvector components can be written as follows:

$$\left(U^{0(5)},\varphi^{0(5)},\psi^{0(5)}\right)=\left(\frac{e\alpha-h\varepsilon}{CK_{em}^2},-\frac{eh}{CK_{em}^2}+\alpha,\frac{e^2}{CK_{em}^2}-\varepsilon\right)=\frac{1}{K_{em}^2}\left(\left(e\alpha-h\varepsilon\right)/C,\alpha\left(K_{em}^2-K_\alpha^2\right),-\varepsilon\left(K_{em}^2-K_e^2\right)\right) \quad (25)$$

Also, the following equalities exist and naturally couple the corresponding eigenvector components:

$$e\varphi^{0(1)}+h\psi^{0(1)}=e\varphi^{0(5)}+h\psi^{0(5)}=e\alpha-h\varepsilon \quad (26)$$

In expression (25), the coefficient of the electromechanical coupling (CEMC) is denoted by K_e^2 and the other parameter denoted by K_α^2 couples only the terms with the electromagnetic constant α in CMEMC (13). They are respectively defined as follows:

$$K_e^2=\frac{e^2}{C\varepsilon} \quad (27)$$

$$K_\alpha^2=\frac{eh}{C\alpha}=\frac{\alpha eh}{C\alpha^2} \quad (28)$$

Utilizing the eigenvalues and the corresponding eigenvectors obtained above, it is possible to compose the complete mechanical displacement U^Σ, complete electrical potential φ^Σ, and complete magnetic potential ψ^Σ. These parameters can be compactly written in the plane wave forms as follows:

$$U^\Sigma=\sum_{p=1,3,5}F^{(p)}U^{0(p)}\exp\left[\mathrm{j}k\left(n_1x_1+n_3^{(p)}x_3-V_{ph}t\right)\right] \quad (29)$$

$$\varphi^\Sigma=\sum_{p=1,3,5}F^{(p)}\varphi^{0(p)}\exp\left[\mathrm{j}k\left(n_1x_1+n_3^{(p)}x_3-V_{ph}t\right)\right] \quad (30)$$

$$\psi^\Sigma=\sum_{p=1,3,5}F^{(p)}\psi^{0(p)}\exp\left[\mathrm{j}k\left(n_1x_1+n_3^{(p)}x_3-V_{ph}t\right)\right] \quad (31)$$

where $F^{(1)}$, $F^{(3)}$, and $F^{(5)}$ are called the weight factors; t is time and j is the imaginary unity, j = $(-1)^{1/2}$. These weight factors must be found when the boundary conditions are applied. The mechanical, electrical, and magnetic boundary conditions are perfectly described in paper (Al'shits *et al*., 1992) for the case of wave propagation in piezoelectromagnetics. The mechanical, electrical, and magnetic boundary conditions used in the study of this paper were mentioned above, namely before this subsection in the beginning of this section.

At the interface between the piezoelectromagnetic medium and a vacuum, the mechanically free surface requires that the normal component of the stress tensor must vanish, namely $\sigma_{32} = 0$. Therefore, the mechanical boundary condition can be expressed as follows:

$$\begin{aligned}\sigma_{32}&=F_1\left[Ck_3^{(1)}U^{0(1)}+ek_3^{(1)}\varphi^{0(1)}+hk_3^{(1)}\psi^{0(1)}\right]\\&+F_2\left[Ck_3^{(3)}U^{0(3)}+ek_3^{(3)}\varphi^{0(3)}+hk_3^{(3)}\psi^{0(3)}\right]\\&+F_3\left[Ck_3^{(5)}U^{0(5)}+ek_3^{(5)}\varphi^{0(5)}+hk_3^{(5)}\psi^{0(5)}\right]\end{aligned} \quad (32)$$

where $F_1 = F^{(1)}$, $F_2 = F^{(3)}$, and $F_3 = F^{(5)}$.

The electrical boundary condition such as continuity of the electrical displacement normal component D_3 at the solid-vacuum interface is written as follows: $D_3 = D^f$, where D^f denotes the electrical induction of a vacuum. The component D_3 is expressed by

$$\begin{aligned}D_3&=F_1\left[ek_3^{(1)}U^{0(1)}-\varepsilon k_3^{(1)}\varphi^{0(1)}-\alpha k_3^{(1)}\psi^{0(1)}\right]\\&+F_2\left[ek_3^{(3)}U^{0(3)}-\varepsilon k_3^{(3)}\varphi^{0(3)}-\alpha k_3^{(3)}\psi^{0(3)}\right]\\&+F_3\left[ek_3^{(5)}U^{0(5)}-\varepsilon k_3^{(5)}\varphi^{0(5)}-\alpha k_3^{(5)}\psi^{0(5)}\right]\end{aligned} \quad (33)$$

The vacuum electrical induction D^f depends on the electrical weight factor F_E as follows:

$$D^f=-F_E\varphi_0^f\,\mathrm{j}k_1\varepsilon_0 \quad (34)$$

The second electrical boundary condition requires continuity of the electrical potential φ at the interface, i.e. $\varphi = \varphi^f$ where

$$\varphi = F_1\varphi^{0(1)} + F_2\varphi^{0(3)} + F_3\varphi^{0(5)} \tag{35}$$

The electrical potential φ^f in a vacuum is

$$\varphi^f = F_E\varphi_0^f \tag{36}$$

It is also possible to discuss two magnetic boundary conditions at the solid-vacuum interface. The first magnetic boundary condition represents continuity of the magnetic flux normal component B_3: $B_3 = B^f$, where

$$\begin{aligned} B_3 = {} & F_1\left[hk_3^{(1)}U^{0(1)} - \alpha k_3^{(1)}\varphi^{0(1)} - \mu k_3^{(1)}\psi^{0(1)}\right] \\ & + F_2\left[hk_3^{(3)}U^{0(3)} - \alpha k_3^{(3)}\varphi^{0(3)} - \mu k_3^{(3)}\psi^{0(3)}\right] \\ & + F_3\left[hk_3^{(5)}U^{0(5)} - \alpha k_3^{(5)}\varphi^{0(5)} - \mu k_3^{(5)}\psi^{0(5)}\right] \end{aligned} \tag{37}$$

The vacuum magnetic flux B^f depends on the magnetic weight factor F_M as follows:

$$B^f = -F_M\psi_0^f \mathrm{j}k_1\mu_0 \tag{38}$$

The second magnetic boundary condition requires continuity of the magnetic potential ψ at the interface, i.e. $\psi = \psi^f$, where

$$\psi = F_1\psi^{0(1)} + F_2\psi^{0(3)} + F_3\psi^{0(5)} \tag{39}$$

The magnetic potential ψ^f in a vacuum reads:

$$\psi^f = F_M\psi_0^f \tag{40}$$

To clarify the vacuum parameters, it is necessary to state that the elastic constant C_0 of a vacuum is thirteen orders smaller than that for a solid: C_0 = 0.001 Pa (Kiang and Tong, 2010). For that reason, it is too negligible to account it in calculations. Also, the vacuum dielectric permittivity constant is $\varepsilon_0 = 10^{-7}/(4\pi C_L^2) = 8.854187817\times10^{-12}$ [F/m] where $C_L = 2.99782458\times10^8$ [m/s] is the speed of light in a vacuum. The vacuum magnetic permeability constant is $\mu_0 = 4\pi\times10^{-7}$ [H/m] = $12.5663706144\times10^{-7}$ [H/m]. The constant ε_0 is the proportionality coefficient between the vacuum electric induction $\mathbf{D^f}$ and the vacuum electric field $\mathbf{E^f}$: $\mathbf{D^f} = \varepsilon_0\mathbf{E^f}$, where the electric field components can be defined as follows: $E^f_i = -\partial\varphi^f/x_i$. Therefore, the Laplace equation of type $\Delta\varphi^f = 0$ can be written for the electrical potential in a vacuum. Similarly, the constant μ_0 is the proportionality coefficient between the vacuum magnetic induction $\mathbf{B^f}$ and the vacuum magnetic field $\mathbf{H^f}$: $\mathbf{B^f} = \mu_0\mathbf{H^f}$, where the magnetic field components can be defined as follows: $H^f_i = -\partial\psi^f/x_i$. Thus, Laplace's equation of type $\Delta\psi^f = 0$ can be used for the magnetic potential in a vacuum. It is required that both the electrical and magnetic potentials must exponentially vanish in a vacuum far from the free surface of the piezoelectromagnetic material.

Based on the equations corresponding to the mechanical, electrical, and magnetic boundary conditions written above, one can consequently compose the following matrix form of three homogeneous equations:

$$\begin{pmatrix} n_3^{(1)}\left[CU^{0(1)} + e\varphi^{0(1)} + h\psi^{0(1)}\right] & n_3^{(3)}\left[CU^{0(3)} + e\varphi^{0(3)} + h\psi^{0(3)}\right] & n_3^{(5)}\left[CU^{0(5)} + e\varphi^{0(5)} + h\psi^{0(5)}\right] \\ en_3^{(1)}U^{0(1)} - \left(\varepsilon n_3^{(1)} - \mathrm{j}\varepsilon_0\right)\varphi^{0(1)} - \alpha n_3^{(1)}\psi^{0(1)} & en_3^{(3)}U^{0(3)} - \left(\varepsilon n_3^{(3)} - \mathrm{j}\varepsilon_0\right)\varphi^{0(3)} - \alpha n_3^{(3)}\psi^{0(3)} & en_3^{(5)}U^{0(5)} - \left(\varepsilon n_3^{(5)} - \mathrm{j}\varepsilon_0\right)\varphi^{0(5)} - \alpha n_3^{(5)}\psi^{0(5)} \\ hn_3^{(1)}U^{0(1)} - \alpha n_3^{(1)}\varphi^{0(1)} - \left(\mu n_3^{(1)} - \mathrm{j}\mu_0\right)\psi^{0(1)} & hn_3^{(3)}U^{0(3)} - \alpha n_3^{(3)}\varphi^{0(3)} - \left(\mu n_3^{(3)} - \mathrm{j}\mu_0\right)\psi^{0(3)} & hn_3^{(5)}U^{0(5)} - \alpha n_3^{(5)}\varphi^{0(5)} - \left(\mu n_3^{(5)} - \mathrm{j}\mu_0\right)\psi^{0(5)} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{41}$$

where the corresponding n_3 are used instead of $k_3 = kn_3$; $k_1 = kn_1$ where $n_1 = 1$.

It is necessary to state that equations (41) already include the vacuum material parameters such as ε_0 and μ_0. It is clearly seen that equations (41) represent three homogeneous equations in three unknowns representing the weight factors F_1, F_2, and F_3. In equations (41), the vacuum weight factors F_E and F_M are naturally excluded, see the boundary conditions written above. Therefore, it is possible to say that one deals here with three-partial SH-wave propagation (instead of five-partial SH-wave) guided by the free surface of piezoelectromagnetics. This is similar to the SH-wave propagation in pure piezoelectrics (Auld, 1990; Dieulesaint and Royer, 1980; Lardat *et al*., 1971; Farnell and Adler, 1972; Farnell, 1978) where two-partial SH-wave (instead of three-partial) propagates because the vacuum weight factor F_E can be excluded.

To simplify equation (41), it is natural to use equations (11), (17), (24) and (25). Indeed, it is possible to exploit the following equalities that significantly simplify equation (41):

$$CU^{0(1)} + e\varphi^{0(1)} + h\psi^{0(1)} = CU^{0(3)} + e\varphi^{0(3)} + h\psi^{0(3)} = e\alpha - h\varepsilon \tag{42}$$

$$CU^{0(5)} + e\varphi^{0(5)} + h\psi^{0(5)} = \left(e\alpha - h\varepsilon\right)\frac{1 + K_{em}^2}{K_{em}^2} \tag{43}$$

$$eU^{0(1)} - \varepsilon\varphi^{0(1)} - \alpha\psi^{0(1)} = eU^{0(3)} - \varepsilon\varphi^{0(3)} - \alpha\psi^{0(3)} = -\varepsilon\alpha + \alpha\varepsilon = 0 \tag{44}$$

$$eU^{0(5)} - \varepsilon\varphi^{0(5)} - \alpha\psi^{0(5)} = \frac{\alpha e^2 - \varepsilon eh}{CK_{em}^2} + \frac{\varepsilon eh}{CK_{em}^2} - \alpha\varepsilon - \frac{\alpha e^2}{CK_{em}^2} + \varepsilon\alpha = 0 \tag{45}$$

$$hU^{0(1)} - \alpha\varphi^{0(1)} - \mu\psi^{0(1)} = hU^{0(3)} - \alpha\varphi^{0(3)} - \mu\psi^{0(3)} = \varepsilon\mu - \alpha^2 \tag{46}$$

$$hU^{0(5)} - \alpha\varphi^{0(5)} - \mu\psi^{0(5)} = \frac{\alpha eh - \varepsilon h^2}{CK_{em}^2} + \frac{\alpha eh}{CK_{em}^2} - \alpha^2 - \frac{\mu e^2}{CK_{em}^2} + \varepsilon\mu = 0 \tag{47}$$

The utilization of equalities from (42) to (47) and eigenvalues (11) and (17) in the matrix form of three homogeneous equations (41) allows one to rewrite them as the following three equations:

$$(e\alpha - h\varepsilon)\left[F_1 + F_2 + F_3\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right] = 0 \quad (48)$$

$$\alpha\left[F_1 + F_2 + F_3\frac{K_{em}^2 - K_\alpha^2}{K_{em}^2}\right] = 0 \quad (49)$$

$$(F_1 + F_2)\left[\varepsilon(\mu + \mu_0) - \alpha^2\right] + F_3\varepsilon\mu_0\frac{K_{em}^2 - K_e^2}{K_{em}^2} = 0 \quad (50)$$

Comparing three homogeneous equations written in matrix form (41) with their reduced forms obtained in equations from (48) to (50), it is possible to write down the determinant of the coefficient matrix in equations (41) in the following reduced form:

$$\alpha(e\alpha - h\varepsilon)\begin{vmatrix} 1 & 1 & \frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2} \\ 1 & 1 & \frac{K_{em}^2 - K_\alpha^2}{K_{em}^2} \\ \varepsilon(\mu+\mu_0)-\alpha^2 & \varepsilon(\mu+\mu_0)-\alpha^2 & \varepsilon\mu_0\frac{K_{em}^2 - K_e^2}{K_{em}^2} \end{vmatrix} = 0 \quad (51)$$

Matrix determinant (51) is called the determinant of the boundary conditions. It is clearly seen that there are two factors such as α and $(e\alpha - h\varepsilon)$ written before the determinant. The first and second factors came from equations (49) and (48), respectively. According to the well-known rules to work with rows and columns of a determinant, it is natural to write both the common factor for the first row of determinant (51) such as α and that for the second row such as $(e\alpha - h\varepsilon)$ outside determinant (51) for simplicity. This changes nothing. Also, it is possible to do the same for the common factor of the third column of determinant (51) such as $1/K_{em}^2$. However, it was not done in equation (51) because it changes nothing and the reader can easily do it. So, the expansion of matrix determinant (51) leads to the following secular equation:

$$\alpha(e\alpha - h\varepsilon)\times\left\{\frac{K_{em}^2 - K_\alpha^2}{K_{em}^2} - \frac{K_{em}^2 - K_\alpha^2}{K_{em}^2} + \left[\varepsilon(\mu+\mu_0)-\alpha^2\right]\right. \quad (52)$$
$$\left.\times\left[\varepsilon\mu_0\left(\frac{K_{em}^2 - K_e^2}{K_{em}^2} - \frac{K_{em}^2 - K_e^2}{K_{em}^2}\right) + \sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\left(\frac{1+K_{em}^2}{K_{em}^2} - \frac{1+K_{em}^2}{K_{em}^2}\right)\right]\right\} = 0$$

As a general rule, secular equation (52) must vanish only for some certain value of the phase velocity V_{ph}. This certain velocity V_{ph} represents the speed of new SH-wave propagating in the transversely isotropic piezoelectromagnetic material of class 6 *mm*. However, it is clearly seen in equation (52) that equality (52) is valid for any value of the velocity V_{ph} because the first and second columns of determinant (51) are identical. So, it is possible to state that there is the uncertainty that represents a peculiarly of finding of suitable speed of new SH-SAW. The suitable SH-SAW speed must indeed satisfy the following inequality: $0 < V_{ph} < V_{tem}$. However, this uncertainty can be resolved below.

Using $F = F_1 + F_2$, it is possible to rewrite equations from (48) to (50) as follows:

$$(e\alpha - h\varepsilon)\left[F + F_3\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right] = 0 \quad (53)$$

$$\alpha\left[F + F_3\frac{K_{em}^2 - K_\alpha^2}{K_{em}^2}\right] = 0 \quad (54)$$

$$F\left[\varepsilon(\mu + \mu_0) - \alpha^2\right] + F_3\varepsilon\mu_0\frac{K_{em}^2 - K_e^2}{K_{em}^2} = 0 \quad (55)$$

It is apparent that equations from (48) to (50) are identical to equations from (53) to (55) due to $F = F_1 + F_2$. However, equations from (53) to (55) have one very important peculiarity: there is already no uncertainty of the phase velocity V_{ph} for these equations because they represent three homogeneous equations in two unknown weight factors such as F and F_3. Indeed, it is well-known that three equations from (53) to (55) can be consistent with each other when one equation represents a sum of two others. This is the condition to determine the weight factors F and F_3. So, the following subsection acquaints the reader with already found natural solution representing the new SH-SAW discovered in book by Zakharenko (2010). However, the main purpose of this theoretical work is to additionally discover some new SH-SAWs. Finally, some incorrect solutions recently found in papers (Wang *et al*., 2007; Liu *et al*., 2007) also discussed in the last of this section.

Already discovered new *SH-wave* (Zakharenko, 2010; Zakharenko, 2011b; Zakharenko, 2013a).

It is clearly seen in the first term of equation (55) that the factor at F such as $[\varepsilon(\mu + \mu_0) - \alpha^2]$ can be interpreted as coupling mechanism (16) of CMEMC (13) such as $[\varepsilon\mu - \alpha^2]$ and there is also the coupling with the vacuum parameter μ_0. Therefore, it is possible to treat coupling mechanism (16) in this subsection. For this purpose, it is natural to multiply equation (48) by $\varepsilon(\mu + \mu_0)/(e\alpha - h\varepsilon)$ and to multiply equation (49) by $-\alpha$. As a result, three equations from (53) to (55) can be rewritten in the following forms:

$$\varepsilon(\mu+\mu_0)\left[F\ +F_3\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right]=0 \quad (56)$$

$$-\alpha^2\left[F\ +F_3\frac{K_{em}^2-K_\alpha^2}{K_{em}^2}\right]=0 \quad (57)$$

$$F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]+F_3\varepsilon\mu_0\frac{K_{em}^2-K_e^2}{K_{em}^2}=0 \quad (58)$$

It is flagrant that equations from (56) to (58) are consistent with each other because the left-hand side of equation (58) can become equal to zero as soon as equations (56) and (57) are successively subtracted from equation (58). Also, homogeneous equations (56) and (57) can be transformed into the same equation. Therefore, equation (56) can be transformed by the following way:

$$\varepsilon(\mu+\mu_0)F\ +(0)+\varepsilon(\mu+\mu_0)F_3\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2} \quad (59)$$

$$=\varepsilon(\mu+\mu_0)F\ +\left(-\alpha^2F\ +\alpha^2F\ \right)+\varepsilon(\mu+\mu_0)F_3\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}$$

$$=F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]+\left[\alpha^2F\ +\varepsilon(\mu+\mu_0)F_3\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right]$$

$$=F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]+F_3\left[\alpha^2\frac{K_{em}^2-K_\alpha^2}{K_{em}^2}+\varepsilon(\mu+\mu_0)\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right]=0$$

The initial equation in equalities (59) demonstrates that zero can be added to the left-hand side of equation (56) and as a result, nothing is changed. However, this zero can be written as $(\alpha^2F-\alpha^2F)=0$. Then, it is demonstrated that the terms such as $(-\alpha^2F)$ and (α^2F) can be grouped with the first and last terms, respectively, and the term with F_3 borrowed from equation (57) can be finally written instead of (α^2F).

Using equation (56), similar transformations can be carried out for equation (57) as follows:

$$-\alpha^2F\ +(0)-\alpha^2F_3\frac{K_{em}^2-K_\alpha^2}{K_{em}^2} \quad (60)$$

$$=-\alpha^2F\ +\left(F\,\varepsilon(\mu+\mu_0)-F\,\varepsilon(\mu+\mu_0)\right)-\alpha^2F_3\frac{K_{em}^2-K_\alpha^2}{K_{em}^2}$$

$$=F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]-\left[F\,\varepsilon(\mu+\mu_0)+\alpha^2F_3\frac{K_{em}^2-K_\alpha^2}{K_{em}^2}\right]$$

$$=F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]+F_3\left[\alpha^2\frac{K_{em}^2-K_\alpha^2}{K_{em}^2}+\varepsilon(\mu+\mu_0)\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right]=0$$

So, transformations (59) and (60) have solidly demonstrated that equations (56) and (57) can be readily transformed into the same equation: see the final expressions in transformations (59) and (60). Therefore, the following two equations in two unknowns can be written instead of three equations from (56) and (57) in two unknowns:

$$F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]+F_3\left[\alpha^2\frac{K_{em}^2-K_\alpha^2}{K_{em}^2}+\varepsilon(\mu+\mu_0)\frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right]=0 \quad (61)$$

$$F\left[\varepsilon(\mu+\mu_0)-\alpha^2\right]+F_3\varepsilon\mu_0\frac{K_{em}^2-K_e^2}{K_{em}^2}=0 \quad (62)$$

Equations (61) and (62) represent already a convenient form to determine the SH-SAW speed and the unknown weight factors F and F_3. To determine the SH-SAW velocity, it is necessary to subtract equation (61) from equation (62), or vice versa. It is thought that it is convenient to determine F and F_3 from equation (62), where F_3 represents the coefficient at F with an opposite sign and F represents the coefficient at F_3. Also, the velocity of the new SH-SAW recently discovered in book by Zakharenko, 2010 (see the new SH-SAW velocity denoted by V_{new1} and defined by equation (108) in the book) can be written in the following explicit form:

$$V_{new1}=V_{tem}\left[1-\left(\frac{K_{em}^2-K_e^2+\alpha^2C_L^2\dfrac{\varepsilon_0}{\varepsilon}\left(K_{em}^2-K_\alpha^2\right)}{\left(1+K_{em}^2\right)\left(1+\dfrac{\mu}{\mu_0}\right)}\right)^2\right]^{1/2} \quad (63)$$

It is clearly seen in expression (63) that the velocity V_{new1} depends on the speed of light in a vacuum defined by

$$C_L^2=\frac{1}{\varepsilon_0\mu_0} \quad (64)$$

The velocity V_{new1} represents one of seven new SH-SAWs recently discovered in book by Zakharenko, 2010. This new SH-SAW can propagate along the free surface of the transversely isotropic piezoelectromagnetics of class 6 *mm*. Also, it is natural to demonstrate that when the piezoelectric constant $e = 0$ and the electromagnetic constant $\alpha = 0$, the PEM SH-SAW defined by expression (63) reduces to the well-known velocity V_{BGpm} of the surface Bleustein-Gulyaev waves (Bleustein, 1968; Gulyaev, 1969) propagating in a pure piezomagnetics.

$$V_{BGpm}=V_{tm}\left[1-\left(\frac{K_m^2}{\left(1+K_m^2\right)\left(1+\mu/\mu_0\right)}\right)^2\right]^{1/2} \quad (65)$$

where V_{tm} and K_m^2 stand for the SH-BAW velocity coupled with the magnetic potential and coefficient of the magnetomechanical coupling (CMMC), respectively.

These very important material characteristics of a pure piezomagnetics are defined by the following expressions:

$$V_{tm} = V_{t4}\left(1 + K_m^2\right)^{1/2} \quad (66)$$

$$K_m^2 = \frac{h^2}{\mu C} \quad (67)$$

In expression (66), the velocity V_{t4} is defined by expression (10).

The following subsection shows two additions new solutions representing two new SH-SAWs that can exist for the boundary conditions studied in this work. The first additional solution also corresponds to coupling mechanism (16) of CMEMC (13) such as ($\varepsilon\mu - \alpha^2$) and the second corresponds to coupling mechanism (15) of CMEMC (13) such as ($e\alpha - h\varepsilon$).

The discovery of the additional new PEM SH-waves

Similar to the theory developed above for the SH-wave propagation in the piezoelectromagnetics, in this subsection the following mechanical, electrical, and magnetic boundary conditions must be satisfied at the vacuum-solid interface: $\sigma_{32} = 0$, $\varphi = \varphi^f$, $D = D^f$, $\psi = \psi^f$, and $B = B^f$. Like the developments carried out in the previous subsection, it is also possible to start with the analysis of three homogeneous equations from (53) to (55). It is necessary to state that this subsection treats the second possibility for coupling mechanism (16) of CMEMC (13) such as $[\varepsilon\mu - \alpha^2]$ when there is the coupling with the vacuum parameter μ_0. Therefore, equation (55) with the factor at F such as $[\varepsilon(\mu + \mu_0) - \alpha^2]$ is the main equation for this case. This main equation must couple equations (53) and (54) together forming a system of three homogeneous equations in two unknown weight factors F and F_3. In order that these three equations become consistent with each other, it is natural to multiply equation (48) by $(\varepsilon\mu - \alpha^2)/(e\alpha - h\varepsilon)$ and to multiply equation (49) by $\varepsilon\mu_0/\alpha$. So, three equations from (53) to (55) have the following final forms:

$$\left(\varepsilon\mu - \alpha^2\right)\left[F + F_3\frac{1 + K_{em}^2}{K_{em}^2}\sqrt{1 - \left(\frac{V_{ph}}{V_{tem}}\right)^2}\right] = 0 \quad (68)$$

$$\varepsilon\mu_0\left[F + F_3\frac{K_{em}^2 - K_\alpha^2}{K_{em}^2}\right] = 0 \quad (69)$$

$$F\left[\varepsilon\left(\mu + \mu_0\right) - \alpha^2\right] + F_3\varepsilon\mu_0\frac{K_{em}^2 - K_e^2}{K_{em}^2} = 0 \quad (70)$$

It is blatant that equations (68) and (69) can be transformed in the similar manner used for the transformation of equations (56) and (57) carried out in the previous subsection. These transformations lead to the system of two equations in two unknowns instead of three equations in two unknowns. Indeed, it is convenient to deal with two equations in two unknowns. These transformations correspond to a sum of equations (68) and (69) resulting in a single equation. Thus, the resulting system of two equations reads:

$$F\left[\varepsilon\left(\mu + \mu_0\right) - \alpha^2\right] + F_3\left[\varepsilon\mu_0\frac{K_{em}^2 - K_\alpha^2}{K_{em}^2} + \left(\varepsilon\mu - \alpha^2\right)\frac{1 + K_{em}^2}{K_{em}^2}\sqrt{1 - \left(\frac{V_{ph}}{V_{tem}}\right)^2}\right] = 0 \quad (71)$$

$$F\left[\varepsilon\left(\mu + \mu_0\right) - \alpha^2\right] + F_3\varepsilon\mu_0\frac{K_{em}^2 - K_e^2}{K_{em}^2} = 0 \quad (72)$$

where the weight factors F and F_3 can be determined from equation (72).

The velocity V_{new8} of the new SH-wave is therefore obtained by a subtraction of equation (72) from equation (71), or vice versa. Also, the velocity V_{new8} can be obtained by a successive subtraction of equations (68) and (69) from equation (70). Thus, the value of the new SH-wave velocity V_{new8} can be evaluated with the following formula:

$$V_{new8} = V_{tem}\left[1 - \left(\frac{\varepsilon\mu_0}{\varepsilon\mu - \alpha^2}\frac{K_e^2 - K_\alpha^2}{1 + K_{em}^2}\right)^2\right]^{1/2} \quad (73)$$

It is worth noting that the obtained explicit form of the new SH-wave velocity V_{new8} given by expression (73) represents the discovery of this theoretical work. Indeed, one can find that solution (73) was not treated in book by Zakharenko (2010). This is so because the author of book (Zakharenko, 2010) has treated the SH-wave propagation in PEM plates (Zakharenko, 2012b) and the research of book by Zakharenko (2012b) allows the author to assume that solution (73) for plate SH-wave propagation is more preferable and convenient than solution (63). Also, it is clearly seen that solution (73) looks like simple one in comparison with solution (63). However, solution (73) has a very interesting peculiarity such as the new SH-SAW defined by expression (73) cannot exist for small values of the electromagnetic constant α because $K_\alpha^2(\alpha \to 0) \to \infty$ occurs. It is obvious that the expression under the square root in formula (73) should have a positive sign in order to deal with real SH-SAW velocity. This peculiarity is absent for solution (63) that can exist for very small values of the electromagnetic constant α, even for $\alpha = 0$.

In addition, it is possible to consider the second case that also leads to discovery of new SH-SAW. The author of book by Zakharenko (2012c) has studied the interfacial SH-wave propagation guided by the common interface between two dissimilar piezoelectromagnetics. One can find in book by Zakharenko (2012c) that coupling mechanisms (14) and (15) of CMEMC (13) such as ($e\mu - h\alpha$) and ($e\alpha - h\varepsilon$) can play the main role. Therefore, it is also possible in this subsection to treat coupling mechanism (15) such as ($e\alpha - h\varepsilon$) for the case of the SH-SAW propagation guided by the free surface of piezoelectromagnetics of class 6 *mm*. For this purpose, it is necessary to treat equation (48) as the main equation that couples equations (49) and (50) in a system of three homogeneous equations. It is blatant that these three equations and therefore, three equations from (53) to (55) can be consistent with each other when equation (53) represents a sum of equations (54) and (55). To get the consistent case, it is necessary to multiply equation (54) by the piezoelectric constant e because it already has the factor such as the electromagnetic constant α and to multiply equation (54) by $-h\varepsilon/[\varepsilon(\mu + \mu_0) - \alpha^2]$. As a result, three equations from (53) to (55) can be rewritten in the following dependable forms:

$$(e\alpha - h\varepsilon)\left[F + F_3 \frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right] = 0 \quad (74)$$

$$e\alpha\left[F + F_3 \frac{K_{em}^2 - K_{\alpha}^2}{K_{em}^2}\right] = 0 \quad (75)$$

$$-h\varepsilon\left[F + F_3 \frac{\varepsilon\mu_0}{\varepsilon(\mu+\mu_0)-\alpha^2}\frac{K_{em}^2 - K_e^2}{K_{em}^2}\right] = 0 \quad (76)$$

Similar to the transformations carried out in the previous subsection, the system of three equations from (74) to (76) can be written as a system of two corresponding equations. Indeed, a sum of equations (75) and (76) gives the second suitable equation. As a consequence, two final homogeneous equations read:

$$(e\alpha - h\varepsilon)\left[F + F_3 \frac{1+K_{em}^2}{K_{em}^2}\sqrt{1-\left(\frac{V_{ph}}{V_{tem}}\right)^2}\right] = 0 \quad (77)$$

$$F(e\alpha - h\varepsilon) + F_3\left[e\alpha\frac{K_{em}^2 - K_{\alpha}^2}{K_{em}^2} - h\varepsilon\frac{\varepsilon\mu_0}{\varepsilon(\mu+\mu_0)-\alpha^2}\frac{K_{em}^2 - K_e^2}{K_{em}^2}\right] = 0 \quad (78)$$

These equations result in the following quite complicated form for the velocity V_{new9} of the ninth new SH-SAW:

$$V_{new9} = V_{tem}\left[1-\left(\frac{e\alpha}{e\alpha - h\varepsilon}\frac{K_{em}^2 - K_{\alpha}^2}{1+K_{em}^2} - \frac{h\varepsilon}{e\alpha - h\varepsilon}\frac{\varepsilon\mu_0}{\varepsilon(\mu+\mu_0)-\alpha^2}\frac{K_{em}^2 - K_e^2}{1+K_{em}^2}\right)^2\right]^{1/2} \quad (79)$$

For the case of a very small value of the electromagnetic constant α, $\alpha \to 0$, explicit form (79) reduces to the following expression:

$$V_{new9\_0} = V_{tem0}\left[1-\left(\frac{K_e^2}{1+K_e^2+K_m^2} + \frac{K_m^2}{(1+K_e^2+K_m^2)(1+\mu/\mu_0)}\right)^2\right]^{1/2} \quad (80)$$

because

$$K_{em}^2(\alpha \to 0) \to K_e^2 + K_m^2 \quad (81)$$

$$V_{tem0} = V_{t4}\left(1+K_e^2+K_m^2\right)^{1/2} \quad (82)$$

It is clearly seen in expression (80) that it reduces to expression (65) for the velocity V_{BGpm} of the surface Bleustein-Gulyaev waves (Bleustein, 1968; Gulyaev, 1969) propagating in a pure piezomagnetics as soon as the piezoelectric constant e vanishes.

So, it is possible to conclude that the consideration of coupling mechanism (15) of CMEMC (13) such as ($e\alpha - h\varepsilon$) results in the new SH-SAW propagating with the velocity V_{new9} defined by formula (79). It is noted that coupling mechanisms (14) of CMEMC (13) such as ($e\mu - h\alpha$) is also possible and will be researched in the future. Solutions (63), (73), and (79) are based on the natural coupling mechanisms of the CMEMC and therefore, are true. However there are also some incorrect solutions for the problem of SH-wave propagation guided by the free surface of piezoelectromagnetics. To discuss them is the main purpose of the following subsection.

The existing incorrect solutions (Wang *et al*., 2007; Liu *et al*., 2007; Zakharenko, 2013a)

Review paper by Zakharenko (2013a) has mentioned some incorrect solutions (Wang *et al*., 2007; Liu *et al*., 2007) for the problem of SH-wave propagation guided by the free surface of a PEM material of class 6 *mm* when the following mechanical, electrical, and magnetic boundary conditions must be satisfied at the interface between a vacuum and the PEM medium: $\sigma_{32} = 0$, $\varphi = \varphi^f$, $D = D^f$, $\psi = \psi^f$, and $B = B^f$, where the superscript "f" is for a vacuum. It is possible to concisely develop the discussions of paper by Zakharenko (2013a) concerning the incorrect results obtained in papers (Wang *et al*., 2007; Liu *et al*., 2007).

The authors of theoretical works (Wang *et al*., 2007; Liu *et al*., 2007) have used the other theoretical methods leading to the following solutions that are different from true solutions given above by formulae (63), (73), and (79):

$$V_{fake} = V_{tem}\left[1-\left(\frac{\frac{\varepsilon_0}{\varepsilon}\left(K_{em}^2-K_m^2\right)+\frac{\mu_0}{\mu}\left(K_{em}^2-K_e^2\right)+\frac{\varepsilon_0\mu_0}{\varepsilon\mu}K_{em}^2}{\left(1+K_{em}^2\right)\left(1-\delta+\frac{\varepsilon_0\mu_0}{\varepsilon\mu}+\frac{\varepsilon_0}{\varepsilon}+\frac{\mu_0}{\mu}\right)}\right)^2\right]^{1/2} \quad (83)$$

In expression (83), one can find that paper (Wang *et al*., 2007) provides $\delta = 0$ in the denominator and paper (Liu *et al*., 2007) offers $\delta = \alpha^2/(\varepsilon\mu)$. So, it is necessary here to state that their incorrect results also differ from each other. Review paper by Zakharenko (2013a) has demonstrated that expression (83) is incorrect because it looks like it was obtained by mixing two different eigenvectors. In addition to the conclusion done in (Zakharenko, 2013a), it is possible also to state that the authors of papers (Wang *et al*., 2007; Liu *et al*., 2007) did not demonstrate that they have found suitable eigenvectors. It is worth noting that to find all the suitable eigenvalues and the corresponding eigenvectors is the main mathematical procedure to resolve the coupled equations of motion. Therefore, papers (Wang *et al*., 2007; Liu *et al*., 2007) did not demonstrate any solutions for the coupled equations of motion. This means that this fact allows one to make a statement that two incorrect solutions given by expression (83) looks like fake solutions.

CONCLUSION

This research work acquaints the reader with the new possible solutions for the problem of the propagation of new SH-SAWs guided by the free surface of the transversely isotropic piezoelectromagnetic (composite) materials of class 6 *mm*. These new solutions corresponding to the new SH-SAWs naturally came from the analysis of the possible coupling mechanisms in the coefficient of the magnetoelectromechanical coupling (CMEMC). It is also discussed the other incorrect solutions recently obtained in the theoretical works (Wang *et al*., 2007; Liu *et al*., 2007). The results obtained in this paper can be useful for experimental investigations of the SH-wave propagation in bulk piezoelectromagnetic homogeneous samples, piezoelectromagnetic plates, and layered structures consisting of dissimilar materials. It is apparent that the obtained results can be also useful for the constitution of various technical devices and correct theoretical descriptions of patent applications.

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Received: May 8, 2013; Revised: Aug 14, 2013;
Accepted: Aug 17, 2013