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ON EXISTENCE OF NEW DISPERSIVE FOUR-POTENTIAL SH-WAVES IN 6 *mm* PLATES FOR NEW COMMUNICATION ERA BASED ON GRAVITATIONAL PHENOMENA

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ABSTRACT

One of the possible ways to further miniaturize technical devices is the utilization of the two-dimensional structures such as plates. The acoustic wave propagation is one of the important characteristics. This theoretical work provides two new shear-horizontal (SH) dispersive acoustic waves. The SH-wave dispersion relations are obtained in explicit forms for the case of the transversely isotropic (6 *mm*) plates. In the plate, the propagation of either new SH-wave is coupled with the electrical, magnetic, gravitational, and cogravitational potentials. Using the obtained SH-waves, it is possible to constitute various technical devices (filters, sensors, etc.) of acoustoelectronics and spintronics, and to integrate them in the new communication era based on some gravitational phenomena. Also, the plate SH-waves are apt for nondestructive testing and evaluation of (composite) thin films.

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INTRODUCTION

The recent theoretical work by Zakharenko (2016) has developed the theory of propagation of specific shear-horizontal surface acoustic wave (SH-SAW) in the transversely isotropic (6 *mm*) materials. The propagation of this new SH-SAW is coupled with the electrical, magnetic, gravitational (gravitoelectric), and cogravitational (gravitomagnetic) potentials. The development of the theory of the SH-wave propagation allows one to study some interactions among the mechanical, electrical, magnetic, gravitational, and cogravitational subsystems. Taking into account the last two subsystems for the SH-wave propagation can build a bridge among the acoustoelecronics, spintronics (the future electronics without free charge carriers) and the new communication era based on some gravitational phenomena.

Füzfa (2016) has recently evaluated the coupling between the gravitational and magnetic fields in an order of by about 10^{-35}. This interaction is extremely weak but can be measured in a laboratory at the Earth conditions with an atomic interferometry experimental technique. So, Füzfa's work is directed towards the control of the gravitational field by the magnetic field. It is expected that many new applications concerning telecommunications with gravitational waves can be realized. The problems of interactions between the gravitational and electromagnetic waves, i.e. the production, detection, and controlling of gravitational fields can certainly represent one of the major interests in modern physics. It is well-known that the speed of light in a solid continuum is approximately five orders larger than the speed of any acoustic wave. This fact allows application the quasi-static approximation in the theoretical treatments. In 2016, it was experimentally recorded that the gravitational waves predicted by Einstein (1916) can also propagate with the speed of light in a vacuum (Abbott *et al*., 2016). The analogy between Maxwell's theory of electromagnetism and gravitation was first discussed by Heaviside (1893). Another study, Füzfa (2016) has also mentioned that the equivalence principle of Einstein's general relativity states that all types of energy produce gravitation and gravitational fields can be created by generating electromagnetic fields.

Regarding some remarkable investigations, it is possible to mention some achievements of Li's research group. Li and Torr (1991) have presented Maxwell's equations for

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gravitation in a form where the superconductor cogravitational (gravitomagnetic) permeability is different from the vacuum one. With superconductors, they have illuminated an interrelationship between the cogravitational and magnetic fields. They have also found that some mass current can be caused by an electrical current and the superconductor magnetic flux represents a function of the cogravitational permeability, and vice versa. It was also shown for superconductors that the magnetically created cogravitational field can be approximately eleven orders larger than the internal magnetic field. Li and Torr (1992) have continued discussions on the interrelationship between the magnetic and cogravitational fields in superconductors. They have found that the propagation velocity of a gravitational wave in a superconductor is two orders of magnitude slower than the vacuum velocity and the value of relative cogravitational permeability is by about four orders larger than the vacuum one. Torr and Li (1993) have studied some coupling between the gravitational (gravitoelectric) and electric fields via superconductivity. Li *et al*. (1997) have recorded very small effect of change in gravity. Kleidis *et al*. (2010) and Forsberg *et al*. (2010) have studied some problems of interactions between gravitational and electromagnetic waves. Hegarty (1969) has evaluated the production effect of the gravitational field by a pulse of electromagnetic radiation.

This study is aimed to take into account all five fields (mechanical, electrical, magnetic, gravitational, and cogravitational) in the theoretical treatments for the SH-wave propagation in thin films, i.e. plates. So, the developed theory in the following section provides the explicit forms for the velocities of the new four-potential dispersive SH-waves propagation in the two-dimensional continuous materials such as plates.

RESULTS AND DISCUSSION

Theoretical Results

First of all, it is necessary to state that the developed theory in (Zakharenko, 2016) provides the results on the propagation of the new nondispersive shear-horizontal surface acoustic wave (SH-SAW) in continuous media, i.e. bulk materials. This new SH-SAW is coupled with the following four potentials: the electrical, magnetic, gravitational, and cogravitational potentials. So, the theoretical work by Zakharenko (2016) records the possible propagation of the new nondispersive 4P-SH-SAW. The results obtained in (Zakharenko, 2016) for the nondispersive wave can be further developed for the investigation of propagation of dispersive 4P-SH-wave in the transversely isotropic (6 *mm*) plates. To study dispersive wave propagation represents a significantly more complicated problem because the layer thickness of the plate plays a role of an additional dimension. Therefore, it is unnecessary in this short report to write down all the complicated formulae for the case of dispersive wave propagation in plates. Indeed, this is needless because the experienced reader can use the developed theory in (Zakharenko, 2016) in order to construct the dispersive wave case from the non dispersive wave one. However, it is indispensable to review the complicated theoretical methods leading to the final results obtained below. So, it is now possible to start the consideration of the dispersive wave propagation.

Consider the two-dimensional transversely isotropic material of 6 *mm* symmetry. Let's use $2d$ for the plate thickness. For the 6 *mm* material of thickness $2d$, the propagation direction must be along the free surface of the plate and perpendicular to the 6-fold symmetry axis of the plate material (Gulyaev, 1998). For this case, the rectangular coordinate system is used: the x_1-, x_2-, and x_3-axes are managed along the propagation direction of the plate waves, 6-fold symmetry axis, and surface normal, respectively. The upper and lower free surfaces of the plate are then situated at $x_3 = + d$ and $x_3 = - d$, respectively. The propagation direction is similar to the case of the 6 *mm* piezoelectrics (Gulyaev, 1998) and 6 *mm* piezoelectromagnetics (Zakharenko, 2013a). The suitable directions for the SH-wave propagation in the piezoelectrics of 6 *mm* symmetry are well-known. The reader can also find them in two bibles (Auld, 1990) and (Dieulesaint and Royer, 1980) for acousticians.

For the wave propagation treatment, it is necessary to first write down the constitutive relations and to apply quasi-static approximation for construction of the differential form of the coupled equations of motion in the common form. These coupled seven equations are quite complicated and therefore, it is unnecessary to delineate them here below because the reader can find them in the recently developed theory (Zakharenko, 2016). The solutions for these complicated equations are naturally inscribed in the plane wave form. Exploiting these solutions for the differential form of the coupled equations of motion, the matrix form of these coupled equations of motion called the modified Green-Christoffel equation (Zakharenko, 2012, 2016) can be obtained. For the suitable propagation direction defined above in the context of this section, the Green-Christoffel equation can be rewritten as two independent sets of equations. The first set of two equations is for the propagation constitution of the purely mechanical in-plane polarized Lamb type wave (Zakharenko, 2007, 2012). The second set of five equations is for the anti-plane polarized SH-wave coupled with the aforementioned four potentials: the electrical, magnetic, gravitational, and cogravitational.

This work has an interest in investigations of the four-potential SH-waves propagating in the transversely isotropic (6 *mm*) plate. Therefore, the set of five coupled equations of motion must be resolved. To resolve the equations' set, it is indispensable to determine all of the ten eigenvalues (Zakharenko, 2016) and the corresponding eigenvectors for each found eigenvalue kn_3 (Zakharenko, 2016, 2017). Here, k is the wave number in the propagation direction and n_3 is called the directional cosine towards the x_3-axis. With all found eigenvalues and eigenvectors, it is possible to write the following complete parameters: the mechanical displacement, electrical potential, magnetic potential, gravitational potential, and co-gravitational potential. Next, it is necessary to utilize these complete parameters in the mechanical, electrical, magnetic, gravitational, and cogravitational boundary conditions. At the upper free surface of the plate, $x_3 = + d$, the normal component of the mechanical stress tensor and all of the four potentials must vanish. The same boundary conditions there are at the lower free surface of the plate, $x_3 = – d$, i.e. the reader deals here with the case of symmetric boundary conditions.

Employing the ten boundary conditions, ten homogeneous equations can be written in the matrix form. Therefore, the tenth order boundary conditions' determinant (BCD10) of the coefficient matrix can be readily constructed. Some transformations usual for the case of plate wave propagation result in the fact that this BCD10 splits into two independent BCD5. Either BCD5 provides the corresponding dispersion relation for the determination of the phase velocity V_{ph} of the new SH-wave coupled with the four potentials. The first dispersion relation, i.e. the dependence of the normalized velocity V_{4Pnew1}/V_{temgc} of the first new dispersive SH-wave can be expressed. This dispersion relation represents the dependence of the normalized velocity V_{4Pnew1}/V_{temgc} on the normalized plate thickness kd, where k is the wavenumber in the propagation direction and d is the plate half-thickness. It is convenient to write down the first dispersion relation in the following forms corresponding to the cases of $V_{4Pnew1} < V_{temgc}$ and $V_{4Pnew1} > V_{temgc}$, respectively:

$$\sqrt{1-\left(V_{4Pnew1}/V_{temgc}\right)^2}\tanh(kd) - \frac{K_{emgc}^2}{1+K_{emgc}^2}\tanh\left(kd\sqrt{1-\left(V_{4Pnew1}/V_{temgc}\right)^2}\right)=0 \quad (1)$$

$$\tanh(kd)\sqrt{\left(V_{4Pnew1}/V_{temgc}\right)^2-1} - \frac{K_{emgc}^2}{1+K_{emgc}^2}\tan\left(kd\sqrt{\left(V_{4Pnew1}/V_{temgc}\right)^2-1}\right)=0 \quad (2)$$

Table 1. The bulk solid material parameters, their estimated values and fundamental physical dimensions.

Material parameter	**Symbol**	**Estimated values**	**Fundamental dimension [kilogram-meter-second]**
Mass density	ρ	10^3 to 10^4	kg/m^3
Elastic stiffness constant	$C = C_{44} = C_{66}$	10^9 to 10^{11}	kg/(m×s^2)
Piezoelectric constant	$e = e_{16} = e_{34}$	0.1 to 10	kg$^{1/2}$/m$^{3/2}$
Piezomagnetic coefficient	$h = h_{16} = h_{34}$	0.1 to 10^3	kg$^{1/2}$/(m$^{1/2}$×s)
Piezogravitic constant	$g = g_{16} = g_{34}$	10^5 to 10^{10}	kg/m^2
Piezocogravitic coefficient	$f = f_{16} = f_{34}$	10^{-16} to 10^{-8}	s^{-1}
Dielectric permittivity coefficient (electric constant)	$\varepsilon = \varepsilon_{11} = \varepsilon_{33}$	10^{-10} to 10^{-8}	s^2/m^2
Magnetic permeability coefficient (magnetic constant)	$\mu = \mu_{11} = \mu_{33}$	10^{-6} to 10^{-3}	dimensionless
Electromagnetic constant	$\alpha = \alpha_{11} = \alpha_{33}$	10^{-16} to 10^{-12}	s/m
Gravitic constant (gravitoelectric permittivity coefficient)	$\gamma = \gamma_{11} = \gamma_{33}$	10^{10} to 10^{11}	kg×s^2/m^3
Cogravitic constant (gravitomagnetic permeability coefficient)	$\eta = \eta_{11} = \eta_{33}$	10^{-28} to 10^{-27}	m/kg
Gravitocogravitic constant	$\vartheta = \vartheta_{11} = \vartheta_{33}$	10^{-16} to 10^{-12}	s/m
Gravitoelectric constant (electrogravitic constant)	$\zeta = \zeta_{11} = \zeta_{33}$	10^{-8} to 10^{-2}	kg$^{1/2}$×s^2/m$^{5/2}$
Cogravitoelectric constant (electrocogravitic constant)	$\xi = \xi_{11} = \xi_{33}$	10^{-45} to 10^{-40}	s/(kg$^{1/2}$×m$^{1/2}$)
Gravitomagnetic constant (magnetogravitic constant)	$\beta = \beta_{11} = \beta_{33}$	10^{-6} to 10	kg$^{1/2}$×s/m$^{3/2}$
Cogravitomagnetic constant (magnetocogravitic constant)	$\lambda = \lambda_{11} = \lambda_{33}$	10^{-40} to 10^{-35}	m$^{1/2}$/kg$^{1/2}$

where

$$V_{temgc} = \sqrt{C\left(1 + K_{emgc}^2\right)/\rho} \tag{3}$$

$$K_{emgc}^2 = \frac{Y_1}{Y_2} \tag{4}$$

$$\begin{aligned}
Y_1 &= e^2\left(\mu\gamma\eta + 2\beta\lambda\vartheta - \lambda^2\gamma - \beta^2\eta - \vartheta^2\mu\right) \\
&+ h^2\left(\varepsilon\gamma\eta + 2\zeta\xi\vartheta - \vartheta^2\varepsilon - \zeta^2\eta - \xi^2\gamma\right) \\
&+ g^2\left(\varepsilon\mu\eta + 2\alpha\xi\lambda - \lambda^2\varepsilon - \alpha^2\eta - \xi^2\mu\right) \\
&+ f^2\left(\varepsilon\mu\gamma + 2\alpha\beta\zeta - \beta^2\varepsilon - \alpha^2\gamma - \zeta^2\mu\right) \\
&+ 2eh\left(\zeta\beta\eta + \xi\gamma\lambda + \vartheta^2\alpha - \alpha\gamma\eta - \zeta\lambda\vartheta - \xi\beta\vartheta\right) \\
&+ 2eg\left(\alpha\beta\eta + \xi\vartheta\mu + \lambda^2\zeta - \alpha\lambda\vartheta - \zeta\mu\eta - \xi\beta\lambda\right) \\
&+ 2ef\left(\alpha\gamma\lambda + \zeta\vartheta\mu + \beta^2\xi - \alpha\beta\vartheta - \zeta\beta\lambda - \xi\mu\gamma\right) \\
&+ 2hg\left(\varepsilon\lambda\vartheta + \zeta\alpha\eta + \xi^2\beta - \alpha\xi\vartheta - \zeta\lambda\xi - \varepsilon\eta\beta\right) \\
&+ 2hf\left(\varepsilon\beta\vartheta + \xi\alpha\gamma + \zeta^2\lambda - \alpha\zeta\vartheta - \zeta\xi\beta - \varepsilon\lambda\gamma\right) \\
&+ 2gf\left(\varepsilon\beta\lambda + \xi\mu\zeta + \alpha^2\vartheta - \alpha\zeta\lambda - \alpha\beta\xi - \varepsilon\mu\vartheta\right)
\end{aligned} \tag{5}$$

$$\begin{aligned}
Y_2 &= C\left(\varepsilon\mu - \alpha^2\right)\left(\gamma\eta - \vartheta^2\right) \\
&+ C\left(\beta^2\xi^2 - \xi^2\mu\gamma - \beta^2\varepsilon\eta\right) + C\left(\lambda^2\zeta^2 - \lambda^2\varepsilon\gamma - \zeta^2\mu\eta\right) \\
&+ 2C\left(\gamma\alpha\xi\lambda + \eta\alpha\beta\zeta + \varepsilon\beta\lambda\vartheta + \mu\zeta\xi\vartheta - \zeta\xi\beta\lambda - \alpha\zeta\lambda\vartheta - \alpha\beta\xi\vartheta\right)
\end{aligned} \tag{6}$$

Expression (3) introduces the velocity V_{temgc} of the shear-horizontal bulk acoustic wave (SH-BAW) coupled with the electrical, magnetic, gravitational, and cogravitational potentials, i.e. the 4P-SH-BAW speed. Expression (4) defines the coefficient of the electromagnetogravito-cogravitomechanical coupling (CEMGCMC) denoted by K_{emgc}^2. All material parameters present in formulae (3), (5), and (6) are listed in Table 1.

Concerning the second dispersion relations for the cases of $V_{4Pnew2} < V_{temgc}$ and $V_{4Pnew2} > V_{temgc}$, the dependences of the normalized velocity V_{4Pnew2}/V_{temgc} of the second new dispersive SH-wave are respectively expressed as follows:

$$\tanh\left(kd\sqrt{1-\left(V_{4Pnew2}/V_{temgc}\right)^2}\right)\sqrt{1-\left(V_{4Pnew2}/V_{temgc}\right)^2} - \frac{K_{emgc}^2}{1+K_{emgc}^2}\tanh(kd) = 0 \tag{7}$$

$$\tan\left(kd\sqrt{\left(V_{4Pnew2}/V_{temgc}\right)^2 - 1}\right)\sqrt{\left(V_{4Pnew2}/V_{temgc}\right)^2 - 1} + \frac{K_{emgc}^2}{1+K_{emgc}^2}\tanh(kd) = 0 \tag{8}$$

To check the rightness of obtained dispersion relations (1) and (7), the reader can use an infinite number of $kd \to \infty$ that soundly leads to the following propagation velocity of the new nondispersive 4P-SH-SAW discovered in (Zakharenko, 2016):

$$V_{new4P} = V_{temgc}\left[1 - \left(\frac{K_{emgc}^2}{1+K_{emgc}^2}\right)^2\right]^{1/2} \tag{9}$$

It is possible to use the coefficient of the electromechanical coupling (CEMC) $K_e^2 = e^2/C\varepsilon$ for a pure piezoelectrics instead of K_{emgc}^2 in formula (9). In this case, formula (9) will reduce to the formula for the calculation of the propagation velocity of the surface Bleustein-Gulyaev wave (Bleustein, 1968; Gulyaev, 1969). This symbolizes that the surface Bleustein-Gulyaev wave coupled with the single potential (electrical or magnetic) is the primitive case compared with the new SH-SAW (9) coupled with the four potentials. It is worth noting that Bleustein and Gulyaev have never treated the gravitational effects. Also, it is possible to utilize the coefficient of the magnetoelectro mechanical coupling (CMEMC) $K_{em}^2 = \left(\mu e^2 + \varepsilon h^2 - 2\alpha e h\right)/C\left(\varepsilon\mu - \alpha^2\right)$ for a piezoelectromagnetic material instead of K_{emgc}^2 in formula (9). This will reduce formula (9) to the formula for the surface Bleustein-Gulyaev-Melkumyan wave (Melkumyan, 2007; Zakharenko, 2013a) coupled with both the electrical and magnetic potentials. These facts of the successful reductions of formula (9) manifest that obtained results (1), (2), (7), (8) in this paper and obtained result (9) in (Zakharenko, 2016) are true. The reader can also check that for obtained results (1), (2), (7), (8), a successive exploitation of all the obtained different twelve sets of the possible eigenvector components (Zakharenko, 2017) do not change these obtained results for the boundary conditions mentioned above formula (1).

The Results of Calculations

Figure 1 shows the dependence of the normalized velocities of the new dispersive SH-waves in the transversely isotropic (6 *mm*) plate. For $K_{emgc}^2 = 0.3$, the relation V_{new4P}/V_{temgc} is equal to by about 0.973 shown in figure 1 by the dotted line. Below the velocity V_{temgc}, the velocity V_{4Pnew1} of the first new SH-wave in the plate starts at some value of kd ~ 4.4 and approaches the velocity V_{new4P} when the value of the normalized plate thickness kd goes to infinity. Also, the normalized velocity V_{4Pnew2}/V_{temgc} of the second new SH-wave starts with $(V_{4Pnew2}/V_{temgc})_{min}$ ~ 0.877 at $kd = 0$ and can reach V_{new4P}/V_{temgc} at a large value of the non-dimensional parameter kd. This fundamental mode cannot exist below the minimum value of $(V_{4Pnew2}/V_{temgc})_{min}$. For the other values of K_{emgc}^2, it is possible to use the graphical results in (Zakharenko, 2014), just use K_{emgc}^2 instead of $K_{em}^2 = \left(\mu e^2 + \varepsilon h^2 - 2\alpha eh\right) / C\left(\varepsilon\mu - \alpha^2\right)$ representing the coefficient of the magnetoelectromechanical coupling for a piezoelectromagnetics.

Dispersion relations (1) and (7) define the phase velocity V_{ph} of the dispersive SH-waves propagating in the plates. Using these dispersion relations, it is possible to find the first ($\mathrm{d}V_{ph}/\mathrm{d}(kd)$) and the higher derivatives of the phase velocity V_{ph} with respect to *kd*. Therefore, it is possible to find the group velocity V_g, the first and the higher derivatives of the V_g with respect to *kd*. According to work (Zakharenko, 2005), the *n-th* derivative of the V_g will be a function of the value of *kd* and both the *n-th* and the (*n*+1)*-th* derivatives of the V_{ph} with respect to *kd*. Thus, the *n-th* derivative (Zakharenko, 2005) is defined by

$$\frac{\mathrm{d}^{(n)}V_g}{\mathrm{d}(kd)^n} = (n+1)\frac{\mathrm{d}^{(n)}V_{ph}}{\mathrm{d}(kd)^n} + kd\frac{\mathrm{d}^{(n+1)}V_{ph}}{\mathrm{d}(kd)^{n+1}} \tag{10}$$

where $n = 0, 1, 2, \ldots, N$. Here there is $V_{ph} = V_{4Pnew1}$ or $V_{ph} = V_{4Pnew2}$.

The calculation of the first derivative of the velocity V_{ph} with respect to *kd* can lead to quite complicated

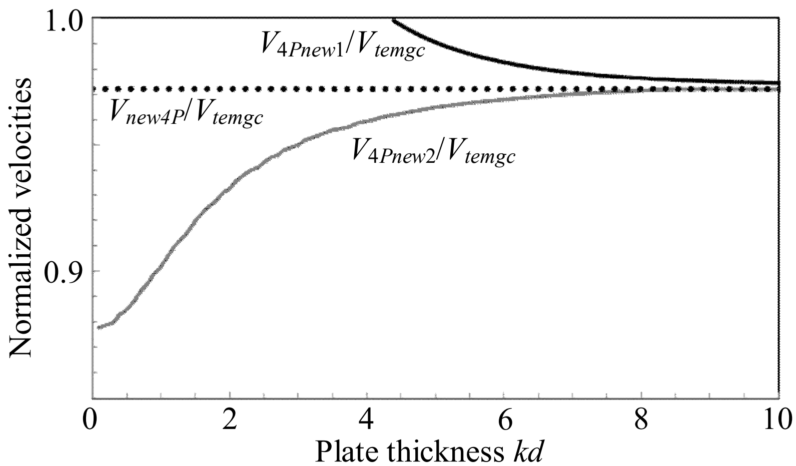

Fig. 1. The dispersion relations for the fundamental modes, where the normalzed velocities V_{4Pnew1}/V_{temgc} (black solid line) and V_{4Pnew2}/V_{temgc} (grey solid line) are defined by equations (1) and (7), respectively; $K_{emgc}^2 = 0.3$.

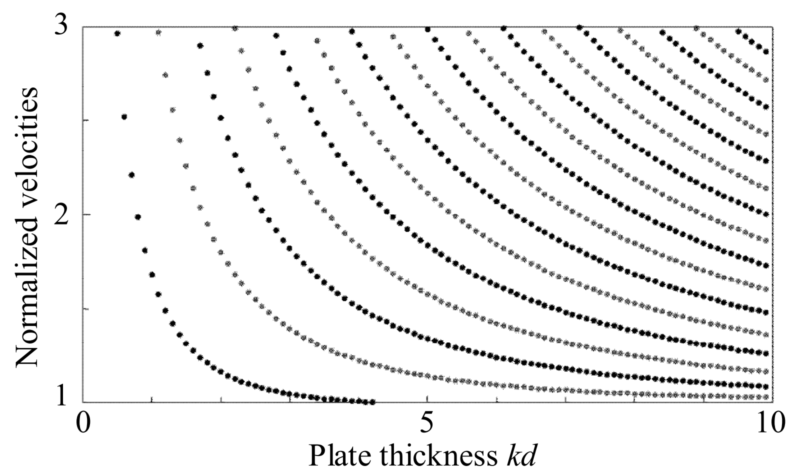

Fig. 2. The dispersion relations for the higher-order modes, where the normalzed velocities V_{4Pnew1}/V_{temgc} (black dotted lines) and V_{4Pnew2}/V_{temgc} (grey dotted lines) are defined by equations (2) and (8), respectively; $K_{emgc}^2 = 0.3$.

expression that is shown in (Zakharenko, 2013b). With $dV_{ph}/d(kd)$, it is possible to calculate the velocity V_g in (10). The second and third derivatives of the velocity V_{ph} with respect to kd can lead to the determination of the first and second derivatives of the velocity V_g. These calculations can result in very large and complicated formulae and therefore, do not represent the main subject of this short report. The work by Zakharenko (2013b) also states that the found first and second derivatives of the velocity V_g can be readily used to determine the extreme and inflexion points in the dependence $V_g(kd)$. The determination of these key points in the dependence $V_g(kd)$ can help in constitution of some technical devices, for instance, the dispersive delay lines for the new era of communication based of some gravitational phenomena.

CONCLUSION

The dispersion relations for two new dispersive 4P-SH-waves propagating in the transversely isotropic (6 *mm*) plates were obtained in explicit analytical forms. The propagation of these new dispersive 4P-SH-waves is coupled with the electrical, magnetic, gravitational, and cogravitational potentials. The obtained dispersion relations were then studied graphically for $K_{emgc}^2 = 0.3$. One of the possible applications is the constitution of new technical devices for new era of communication based on some gravitational phenomena. In comparison with bulk materials, the two-dimensional structures (plates) can further miniaturize the technical devised. The plate SH-waves can be also suitable for nondestructive testing and evaluation.

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