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STUDY OF BLEUSTEIN-GULYAEV SURFACE WAVES IN PIEZOELECTRIC MATERIALS CONTAINING PARALLEL ELECTRODES

Anti-plane shear electro-elastic surface waves are studied in transversely isotropic piezoelectric materials containing two embedded grounded electrodes. The electrodes are considered to be perfectly conducting with negligible thickness and mechanical stiffness. The dispersion equations with respect to the phase velocity for symmetric and anti-symmetric guided modes are derived in analytical forms and discussed in detail. Explicit closed-form expressions are obtained for the solutions of the coupled differential equations for electro-elastic media with corresponding electrode contact conditions. These closed-form solutions represent the mechanical displacement and electric potential of the surface waves in the whole piezoelectric medium. It is shown that the velocities of the guided electro-elastic waves have specific order. The order of the available guided waves and their dependence on structural parameters of the electro-elastic material are studied in detail.

Keywords: *piezoelectric material, surface wave, existence condition, numerical analysis, Bleustein-Gulyaev.*

1. Introduction. Piezoelectric structures with multiple inclusions play important role in microelectromechanical systems. Many surface acoustic wave (SAW) devices and sensors have multi-inclusion structures with the aim of achieving high performance. Surface acoustic wave devices based on piezoelectric effect have been widely used as sensors, actuators, transducers, filters, delay lines, etc. in signal transmission, signal processing, information storage, medical appliance, active vibration and acoustic control applications since the 1970s [1]. This wide application range of piezoelectric materials is related to their electro-mechanical sensitivity, working reliability and stability accompanied by electromechanical coupling and new possibilities for existence of surface waves. The studies of shear acoustic surface waves in piezoelectric materials were initiated by Bleustein [2] and Gulyaev [3] about 40 years ago. The pure shear acoustic surface wave they theoretically predicted has a simple electro-elastic structure and has found many applications in different wave devices. A number of investigations have been conducted on acoustic surface waves in different structures with interconnected electric and elastic fields. Maerfeld and Tournois [4] investigated surface waves at the interface of dissimilar piezoelectric half-spaces with and without a conducting electrode embedded between them, Danicki [5] studied surface waves guided by a single embedded grounded electrode in piezoelectric material, Laprus and Danicki [6] investigated waves propagating along a perfectly conducting plane embedded in a piezoelectric medium, Danoyan and Piliposian [7] considered surface waves in a piezoelectric half-space with hard and soft layers, Li et. al. [8] and Du et. al. [9] investigated Love waves in functionally graded piezoelectric materials, Melkumyan [10] and Wang et. al. [11] contributed to investigation of new surface waves in the presence of coupling between electric, elastic and magnetic fields.

Surface acoustic waves (SAW) propagating along a free surface of a material are widely used in electronic devices. These SAW propagate along a mechanically open surface which must be encapsulated in order to protect the mechanically free surface from the adverse environmental influence. Some interesting crystals cannot be used in such structures only because of their high sensitivity to the environment [6]. However, the encapsulation itself may create new problems leading to disorder of the device. The piezoelectric surface waves that are guided by embedded electrodes are free from these problems and therefore should have greater range of applications.

The purpose of this paper is to continue the systematic detailed investigation of surface waves in piezoelectric materials containing two electrodes started in Bezhanyan et. al. [12]. The electrodes are assumed to be very thin so that their thicknesses and stiffnesses can be neglected. It is shown that depending on the parameters of the structure one or two surface waves can be guided by the embedded electrodes. Explicit expressions are obtained representing the mechanical displacement and electric potential of the surface waves. The order of the available guided waves and their dependence on structural parameters are also studied in detail.

2. Problem statement. Consider a transversely isotropic piezoelectric medium of hexagonal symmetry (e.g. 6mm class), which contains two embedded plane grounded electrodes at a distance $2a$ from each other as shown in Fig. 1. The planes of the electrodes are parallel to each other and to the axis of material symmetry of the piezoelectric media in which they are embedded. A Cartesian coordinate system XYZ is chosen in such a way that the Z axis coincides with the axis of material symmetry and the planes $-\infty < x < +\infty$, $y = a$, $-\infty < z < +\infty$; $-\infty < x < +\infty$, $y = -a$, $-\infty < z < +\infty$ coincide with the planes of the electrodes.

The relevant electro-acoustic coupling is between the anti-plane displacement and the in-plane electric field, i.e

$$\mathbf{u} = \left(0, 0, w(x, y, t)\right),\ \mathbf{E} = \left(-\partial\varphi(x, y, t)/\partial x,\ -\partial\varphi(x, y, t)/\partial y,\ 0\right), \qquad (1)$$

which leads to coupling between SH acoustic waves and TE electric waves.

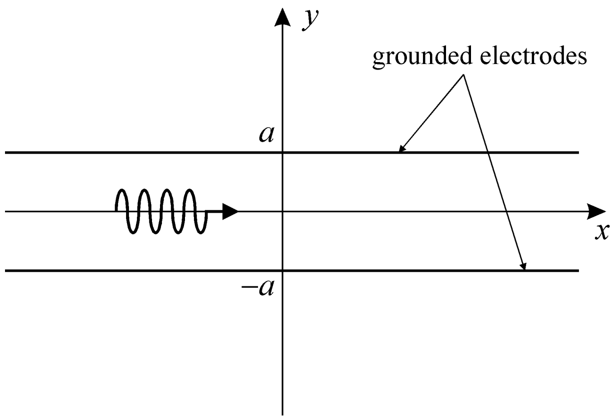

Fig. 1. Parallel grounded electrodes embedded into piezoelectric media

In the framework of the quasi-static approximation the following expressions for the displacement and pseudo-electric potential functions of the electro-elastic field are obtained by Bezhanyan et. al. [12]:

$$w(x,y,t)=e^{ik(x-ct)}\begin{cases}A_1\exp\left[-k\beta(c)(y-a)\right], & y>a\\ A_2\exp\left[-k\beta(c)(y-a)\right]+A_3\exp\left[k\beta(c)(y+a)\right], & -a<y<a\\ A_4\exp\left[k\beta(c)(y+a)\right], & y<-a\end{cases}, \tag{2}$$

$$\phi(x,y,t)=e^{ik(x-ct)}\begin{cases}B_1\exp\left[-k(y-a)\right], & y>a\\ B_2\exp\left[-k(y-a)\right]+B_3\exp\left[k(y+a)\right], & -a<y<a\\ B_4\exp\left[k(y+a)\right], & y<-a\end{cases}, \tag{3}$$

where A_1, A_2, A_3, A_4, B_1, B_2, B_3 and B_4 are unknown coefficients and

$$\beta(c)=\sqrt{1-c^2/c_s^2}\,. \tag{4}$$

Eqs. (2)-(3) lead to a system of eight homogeneous algebraic equations for the unknown coefficients. The existence of nontrivial solution of this linear algebraic system requires that its determinant must vanish, which after some algebraic manipulations leads to the following dispersion equation:

$$\left(F_{sy}(c,h)-k_e^2\right)\left(F_{an}(c,h)-k_e^2\right)=0\,, \tag{5}$$

where $h=ak$ and

$$F_{sy}(c,h)=\beta(c)\left(1+e^{-2h}\right)\Big/\left(1+e^{-2h\beta(c)}\right), \qquad F_{an}(c,h)=\beta(c)\left(1-e^{-2h}\right)\Big/\left(1-e^{-2h\beta(c)}\right). \tag{6}$$

The functions $F_{sy}(c,h)$ and $F_{an}(c,h)$ characterize symmetric and anti-symmetric surface modes, respectively.

3. Existence of surface waves. From the dispersion Eq. (5) it follows that the surface waves that can be guided by the structure under consideration satisfy one of the following equations:

$$F_{sy}(c,h)=k_e^2\,, \tag{7}$$

$$F_{an}(c,h)=k_e^2\,. \tag{8}$$

As the electromechanical coupling coefficient k_e belongs to the interval $(0,1)$, from Eq. (7) it follows that:

a) In case of any h there is exactly one symmetric surface wave mode with velocity of propagation $c_{sy}=c_{sy}(h,k_e)$ which is the unique solution of Eq. (7).

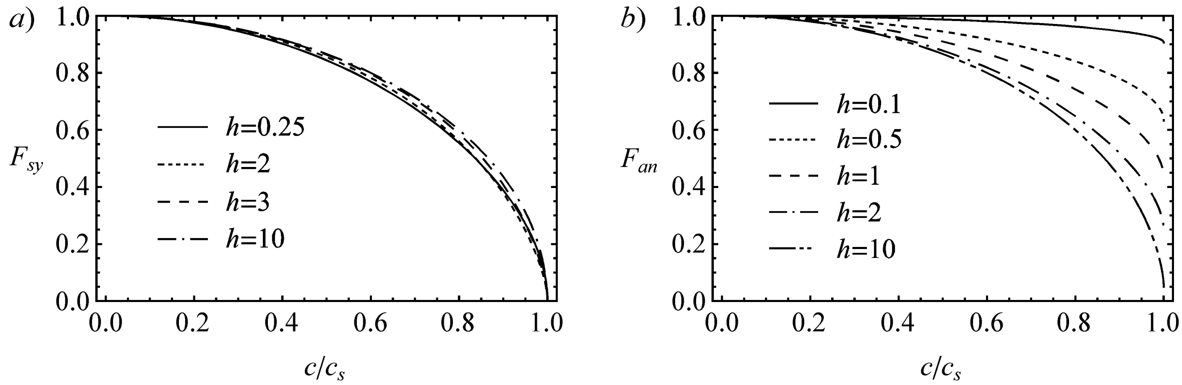

Fig. 2. Variations of the functions a) $F_{sy}(c,h)$ and b) $F_{an}(c,h)$ versus c/c_s for different values of h.

From Eq. (8) it follows that the function $F_{an}(c,h)$ monotonically decreases from 1 to $\left(1-e^{-2h}\right)/2h>0$ when c increases from 0 to c_s (Fig. 2*b*). As $k_e \in (0,1)$ we have:

a) There is no anti-symmetric surface wave mode if $k_e \le k_{e,an}^0$ where

$$k_{e,an}^0 = \sqrt{\left(1-e^{-2h}\right)/2h}\,. \tag{9}$$

b) There is exactly one anti-symmetric surface wave mode if $k_e > k_{e,an}^0$, the propagation velocity $c_{an} = c_{an}(h,k_e)$ of which is the unique solution of Eq. (8).

As the function $\lim_{c\to c_s} F_{an}(c,h)$ monotonically decreases from 1 to 0 when h increases from 0 to ∞, the existence conditions for anti-symmetric surface waves are:

I. There is no anti-symmetric surface wave mode if $h < h_{an}^0(k_e)$.

II. There is exactly one anti-symmetric surface wave mode if $h > h_{an}^0(k_e)$, the propagation velocity $c_{an} = c_{an}(h,k_e)$ of which is the unique solution of Eq. (8).

The $h_{an}^0(k_e)$ is the unique positive solution of the equation:

$$1-\exp\left(-2h_{an}^0\right) = 2h_{an}^0 k_e^2\,. \tag{10}$$

4. Order of surface wave velocities. Using Eqs. (4), (6) and the inequalities

$$\left(1-e^{-2h}\right)/\left(1-e^{-\beta(c)2h}\right) > 1 > \left(1+e^{-2h}\right)/\left(1+e^{-\beta(c)2h}\right) \tag{11}$$

it can be shown that

$$F_{an}(c,h) > \beta(c) > F_{sy}(c,h)\,. \tag{12}$$

From the following:

I. $F_{sy}(c,h)$, $F_{an}(c,h)$, $\beta(c)$ are monotonically decreasing functions of c

II. $F_{sy}(0,h)=1$, $F_{an}(0,h)=1$, $\beta(0)=1$

III. Symmetric wave velocity $c_{sy}(h,k_e)$ is the unique positive solution of Eq. (7) in case of any h. Anti-symmetric wave velocity $c_{an}(h,k_e)$ is the unique positive solution of Eq. (8) when $h > h_{an}^0(k_e)$. The Bleustein-Gulyaev (B-G) surface wave velocity $c_{bg}(k_e)$ is the unique positive solution of the equation $\beta(c) = k_e^2$

we obtain:

$$0 < c_{sy}(h,k_e) < c_{bg}(k_e) < c_s \text{ for any } h\,; \tag{13}$$

$$0 < c_{sy}(h,k_e) < c_{bg}(k_e) < c_{an}(h,k_e) < c_s \text{ when } h > h_{an}^0(k_e)\,. \tag{14}$$

5. Dependence of the guided surface wave velocities on structure parameters. Based on the relations for anti-symmetric and symmetric surface waves we describe the dependences of surface wave velocities on the electro-mechanical coupling coefficient k_e and on $h = ak$. For the anti-symmetric surface wave velocity of propagation we have:

a) $\lim\limits_{k_e\to 1} c_{an}(h,k_e)=0$, $\qquad \lim\limits_{k_e\to(1-e^{-2h})/2h} c_{an}(h,k_e)=c_s$. (15)

b) $\lim\limits_{h\to\infty} c_{an}(h,k_e)=c_{bg}(k_e)$, $\qquad \lim\limits_{h\to h_{an}^0(k_e)} c_{an}(h,k_e)=c_s$. (16)

c) Anti-symmetric surface wave velocity is a monotonically decreasing function of $h=ak$:

$$\partial c_{an}/\partial h<0 \text{ for any } h>h_{an}^0(k_e). \tag{17}$$

d) Anti-symmetric surface wave velocity is a monotonically decreasing function of the electro-mechanical coupling coefficient k_e:

$$\partial c_{an}/\partial k_e<0 \text{ for any } k_e>k_{e,an}^0. \tag{18}$$

For the symmetric surface wave velocity of propagation the results are:

a) $\lim\limits_{k_e\to 1} c_{sy}(h,k_e)=0$, $\qquad \lim\limits_{k_e\to 0} c_{sy}(h,k_e)=c_{el}$. (19)

b) $\lim\limits_{h\to\infty} c_{sy}(h,k_e)=c_{bg}(k_e)$, $\qquad \lim\limits_{h\to 0} c_{sy}(h,k_e)=c_{bg}(k_e)$. (20)

c) There is a value $h=h_{sy}^{\min}(k_e)>0$ such that $c_{sy}(h,k_e)$ monotonously decreases when h increases from 0 to $h_{sy}^{\min}(k_e)$, monotonously increases when h increases from $h_{sy}^{\min}(k_e)$ to ∞ and obtains its minimal value $c_{sy}^{\min}(k_e)$ when $h=h_{sy}^{\min}(k_e)$:

$$\frac{\partial c_{sy}}{\partial h}<0 \text{ if } 0<h<h_{sy}^{\min}(k_e); \qquad \left.\frac{\partial c_{sy}}{\partial h}\right|_{h=h_{sy}^{\min}(k_e)}=0; \qquad \frac{\partial c_{sy}}{\partial h}>0 \text{ if } h>h_{sy}^{\min}(k_e), \tag{21}$$

$$c_{sy}^{\min}(k_e)=c_{sy}\left(h_{sy}^{\min}(k_e),k_e\right)=\min_{h>0} c_{sy}(h,k_e). \tag{22}$$

d) The minimal surface wave velocity $c_{sy}^{\min}(k_e)$ can be calculated as the unique solution of the equation

$$\exp\left[-\frac{\ln\left(1/k_e^2\right)}{1-\beta\left(c_{sy}^{\min}\right)}\right]=\frac{1-k_e^2}{1-\beta\left(c_{sy}^{\min}\right)}-1, \quad 0<c_{sy}^{\min}<c_s \tag{23}$$

and the corresponding $h_{sy}^{\min}(k_e)$ can be determined by the equality

$$h_{sy}^{\min}(k_e)=\ln\left(1/k_e\right)\Big/\left[1-\beta\left(c_{sy}^{\min}\right)\right]. \tag{24}$$

e) Anti-symmetric surface wave velocity of propagation is a monotonically decreasing function of the electromechanical coupling coefficient k_e:

$$\partial c_{sy}/\partial k_e<0 \text{ for any } h \text{ and } k_e. \tag{25}$$

Here c_{el} is the pure shear elastic bulk wave velocity in the absence of piezoelectric effect: $c_{el}=\sqrt{c_{44}/\rho}$.

6. Explicit expressions for surface waves. Once the existence conditions are satisfied, the system of linear algebraic equations for the unknown coefficients A_1, A_2, A_3, A_4, B_1, B_2, B_3 and B_4 can be solved explicitly. Substituting the solution expressions into Eqs. (2)-(3) after some algebraic manipulations we arrive at the following simple explicit expressions for guided surface waves:

symmetric surface wave:

$$w_{sy}(x,y,t) = w_{sy}^{0}\begin{Bmatrix} e^{\beta(c_{sy})(h-k|y|)}, & |y|>a \\ \dfrac{\cosh\left[ky\beta(c_{sy})\right]}{\cosh\left[h\beta(c_{sy})\right]}, & |y|<a \end{Bmatrix}\exp\left[ik\left(x-c_{sy}t\right)\right], \tag{26}$$

$$\phi_{sy}(x,y,t) = -\frac{e_{15}}{\varepsilon_{11}}w_{sy}^{0}\begin{Bmatrix} e^{h-k|y|}, & |y|>a \\ \dfrac{\cosh(ky)}{\cosh(h)}, & |y|<a \end{Bmatrix}\exp\left[ik\left(x-c_{sy}t\right)\right], \tag{27}$$

anti-symmetric surface wave:

$$w_{an}(x,y,t) = w_{an}^{0}\,\mathrm{sgn}(y)\begin{Bmatrix} e^{\beta(c_{an})(h-k|y|)}, & |y|>a \\ \dfrac{\sinh\left[k|y|\beta(c_{an})\right]}{\sinh\left[h\beta(c_{an})\right]}, & |y|<a \end{Bmatrix}\exp\left[ik\left(x-c_{an}t\right)\right], \tag{28}$$

$$\phi_{sy}(x,y,t) = -\frac{e_{15}}{\varepsilon_{11}}w_{an}^{0}\,\mathrm{sgn}(y)\begin{Bmatrix} e^{h-k|y|}, & |y|>a \\ \dfrac{\sinh(k|y|)}{\sinh(h)}, & |y|<a \end{Bmatrix}\exp\left[ik\left(x-c_{an}t\right)\right]. \tag{29}$$

where w_{sy}^{0} and w_{an}^{0} are new arbitrary constants.

From Eqs. (26)-(29) it follows that

$$w_{sy}(x,y,t) \equiv w_{sy}(x,-y,t), \qquad \phi_{sy}(x,y,t) \equiv \phi_{sy}(x,-y,t); \tag{30}$$

$$w_{an}(x,y,t) \equiv -w_{an}(x,-y,t), \qquad \phi_{an}(x,y,t) \equiv -\phi_{an}(x,-y,t) \tag{31}$$

which shows that the components with subscripts '*sy*' and '*an*' represent symmetric and anti-symmetric surface waves, respectively.

7. Conclusions. Shear surface waves that can be guided by parallel grounded electrode inclusions in piezoelectric media are studied in details. An explicit dispersion equation is presented. It is shown that at most a single symmetric and a single anti-symmetric surface wave can be guided by the structure under consideration. Explicit closed-form expressions are obtained for the solutions of the coupled electro-elastic differential equations with corresponding electrode contact conditions. These closed-form solutions represent the mechanical displacement and electric potential of the surface waves in the whole piezoelectric medium. It is shown that the velocities of the guided electro-elastic waves have specific order. The order of the available guided waves and their dependence on structural parameters of the electro-elastic material are studied in detail.

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ԲԼՈՒՍՏԵՅՆ-ԳՈՒԼՅԱԵՎԻ ՄԱԿԵՐԵՎՈՒԹԱՅԻՆ ԱԼԻՔՆԵՐԻ ՈՒՍՈՒՄՆԱՍԻՐՈՒԹՅՈՒՆԸ ԶՈՒԳԱՀԵՌ ԷԼԵԿՏՐՈԴՆԵՐ ՊԱՐՈՒՆԱԿՈՂ ՊԻԵԶՈԷԼԵԿՏՐԱԿԱՆ ՆՅՈՒԹԵՐՈՒՄ

Ուսումնասիրված են հակահարթ էլեկտրաառաձգական մակերևութային ալիքների տարածումը տրանսվերսալ իզոտրոպ պիեզոէլեկտրական նյութերում, որոնք պարունակում են երկու ներդրված հողակցված էլեկտրոդներ: Ենթադրվում է, որ էլեկտրոդներն իդեալական հաղորդիչ են և ունեն անտեսելի հաստություն և մեխանիկական կոշտություն: Ֆազային արագության նկատմամբ դիսպերսիոն հավասարումները տարածվող ալիքի սիմետրիկ և հակասիմետրիկ մասերի համար անալիտիկորեն արտածված և մանրամասն քննարկված են: Բացահայտ փակ արտահայտություններ են ստացված կապակցված էլեկտրաառաձգական դիֆերենցիալ հավասարումների և էլեկտրոդների կոնտակտային պայմանների լուծումների համար: Այս փակ լուծումները ներկայացնում են մակերևութային ալիքի մեխանիկական տեղափոխությունը և էլեկտրական դաշտի պոտենցիալը ամբողջ պիեզոէլեկտրական միջավայրում: Ցույց է տրված, որ տարածվող էլեկտրաառաձգական ալիքների արագությունները ունեն որոշակի հերթականություն: Առկա ալիքների հերթականությունը և նրանց կախվածությունը նյութի պարամետրերից մանրամասն ուսումնասիրված են:

Առանցքային բառեր. *պիեզոէլեկտրական նյութ, մակերևութային ալիք, գոյության պայման, Բլուստեյն-Գուլյան:*

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ИЗУЧЕНИЕ ПОВЕРХНОСТНЫХ ВОЛН БЛЮСТЕЙНА-ГУЛЯЕВА В ПЬЕЗОЭЛЕКТРИЧЕСКИХ МАТЕРИАЛАХ СОДЕРЖАЩИХ ПАРАЛЛЕЛЬНЫЕ ЭЛЕКТРОДЫ

Исследованы антиплоские электроупругие волны в трансверсально изотропных пьезоэлектрических материалах, содержащих два заземленных электродных включения. Предполагается, что электроды являются идеально проводящими и имеют пренебрежительные толщину и механическую жесткость. Аналитически выведены и детально обсуждены дисперсионные уравнения относительно фазовой скорости для симметричных и антисимметричных модельностей распространяющихся волн. Получены явные замкнутые выражения для решений взаимосвязанных дифференциальных уравнений для электро-упругих сред и контактных условий электродов. Эти замкнутые решения представляют механическое перемещение и электрический потенциал поля поверхности волн во всей пьезоэлектрической среде. Показано, что скорости распространяющихся электро-упругих волн имеют определеный порядок. Детально изучены порядок присутствующих волн и их зависимость от параметров материала.

Ключевые слова: *пьезоэлектрический материал, поверхностные волны, условия существования, Блюстейн-Гуляев.*

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