Influence of polymeric nanocomposite film on acoustic waves in piezoelectrics

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At present the attention of researchers is attracted by investigation of multi-layer acoustical waveguides with using of well known as well as novel materials. Also in present time there exist a lot of papers devoted to novel nanocomposite polymeric materials. But the influence of such materials on parameters of acoustic waves in piezoelectrics did not study. In this connection the paper is devoted to theoretical investigation of acoustic waves in structure "piezoelectric – polymeric nanocomposite film". The analysis was carried out by the example of polymeric nanocomposite film with various contents of Fe or CdS nanoparticles and lithium niobate or lithium tantalate plate as substrate. As a result of conducted calculation the velocity and attenuation per wavelength have been found for acoustic waves propagating in aforementioned structures. The conducted analysis has showed that for certain value of nanocomposite film thickness the attenuation of investigated waves has the resonant behavior. The obtained results allow choose such values of film thickness for which the acoustic wave does not practically attenuate in the presence of such film. This opens, for example, the prospects of development of undisturbed substrates of nanocomposite materials for thin piezoelectric plates.

1 Introduction

At present the attention of researchers is attracted by investigation of multi-layer acoustical waveguides with using of well known as well as novel materials [1]. It is connected with the need of development of various sensors and signal processing devices having the given characteristics, the need of creation of various coatings with total absorption of probing radiation, etc.

The development of these directions requires the using the novel materials the properties of which can be changed in their growing process or by various external actions (temperature, electrical and magnetic fields, etc). Such materials may be created on the base of nanocomposite metal-containing polymeric films [2]. It should be noted that mechanical and electrical properties of these materials depend on the concentration of nanoparticles in such films. This fact allows hoping to get the nanocomposite materials with given temperature dependency of dielectric constant. As it is known [3] there exists the possibility of development of the thermostable highly sensitive acoustic sensors based on structure "piezoelectric plate - butyl acetate." The high sensitivity of such sensors is caused by high value of electromechanical coupling coefficient of shear- horizontal (SH_0) waves of zero order in thin piezoelectric plates [4]. At the same time their thermostability is caused by the special liquid (butyl acetate) having the certain temperature dependency of permittivity. However the creation and using of such structure is bound by the certain technological difficulties. In this connection it seems to be interesting to find the material, which can replace butyl acetate. One of such material is nanocomposite polymeric film.

It should be noted that previously the influence of such films on parameters of acoustic waves in such plates practically did not studied. In this connection the paper is devoted to theoretical investigation of SH_0 acoustic waves in structure "piezoelectric plate – polymeric nanocomposite film". The analysis was carried out by the example of polymeric nanocomposite film with various contents of Fe or CdS nanoparticles and $LiTaO_3$ or $LiNbO_3$ plate.

2 The main equations and boundary conditions

The geometry of the problem under consideration is shown in Fig.1. Wave propagates along the x_1 direction of a piezoelectric plate bounded by planes $x_3=0$ and $x_3=h$. The

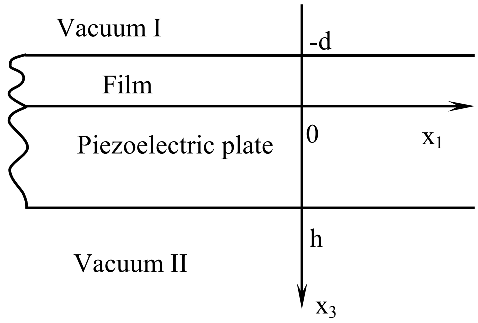

Fig.1 The geometry of the problem.

nanocomposite polymeric film is bounded by planes $x_3 = 0$ and $x_3 = -d$. We consider that this film is viscous, nonconductive and isotropic. The regions $x_3 < -d$ and $x_3 > h$ correspond to vacuum. We consider a two dimensional problem in which all field components are assumed to be constant in the x_2 direction. For analysis of wave propagation we used the motion equation, Laplace's equation, and constitutive equations for piezoelectric medium [5] and polymeric film:

$$\rho \partial^2 U_i / \partial t^2 = \partial T_{ij} / \partial x_j \,, \; \partial D_j / \partial x_j = 0 \,, \qquad (1)$$

$$T_{ij} = C_{ijkl} \, \partial U_l / \partial x_k + e_{kij} \, \partial \Phi / \partial x_k \,, \qquad (2)$$

$$D_j = -\varepsilon_{jk} \, \partial \Phi / \partial x_k + e_{jlk} \, \partial U_l / \partial x_k \,, \qquad (3)$$

$$\rho^f \, \partial^2 U_i^f / \partial t^2 = \partial T_{ij}^f / \partial x_j \,, \partial D_j^f / \partial x_j = 0 \,, \qquad (4)$$

$$T_{ij}^f = C_{ijkl}^f \, \partial U_l^f / \partial x_k + \eta_{ijkl}^f \, \partial U_l^f \partial U_l^f / \partial t \partial x_k \,, \qquad (5)$$

$$D_j^f = -\varepsilon_{jk}^f \, \partial \Phi^f / \partial x_k \,. \qquad (6)$$

Here U_i is the component of mechanical displacement of particles, t is time, T_{ij} is the component of the mechanical stress, x_j is the coordinate, D_j is the component of the electrical displacement, Φ is the electrical potential, ρ is the density, c_{ijkl}, η_{ijkl}, e_{ikl}, and ε_{jk} are the elastic, viscous, piezoelectric, and dielectric constants, respectively. The index f denotes that the appropriate variable refers to polymeric nanocomposite film. Because the considered nanocomposite film is viscoelastic the Eq. (5) shows that the effective elastic constants are complex and their imaginary part is equal $\omega\eta_{ijkl}$ for harmonic waves.

Outside of the structure, in regions I and II, the electrical displacement must satisfy the Laplace's equation:

$$\partial D_j^I / \partial x_j = 0, \quad \partial D_j^{II} / \partial x_j = 0, \qquad (7)$$

where $D_j^I = -\varepsilon_0 \partial \Phi^I / \partial x_j$ and $D_j^{II} = -\varepsilon_0 \partial \Phi^{II} / \partial x_j$. Here, ε_0 is the permittivity of vacuum, indices I and II denote that the values refer to regions $x_3 < -d$ and $x_3 > h$, respectively.

Acoustic waves propagating in aforementioned structure must also satisfy the mechanical and electrical boundary conditions:

$$x_3=-d:\ T_{i3}^f = 0;\ \Phi^f = \Phi^I,\ D_3^f = D_3^I; \quad (8)$$

$$x_3=0:\ U_i^f = U_i;\ T_{i3}^f = T_{i3};\ \Phi^f = \Phi;\ D_3^f = D_3; \quad (9)$$

$$x_3=h:\ T_{i3} = 0;\ \Phi = \Phi^{II};\ D_3 = D_3^{II}. \quad (10)$$

Here i=1÷3, d and h are the thickness of nanocomposite film and piezoelectric plate, respectively.

We used the material constants of lithium tantalate and lithium niobate from [6]. The material constants of nanocomposite polymeric film containing various concentrations of Fe or CdS nanoparticles have been measured by authors using method [7] and they are shown in Tables 1 and 2 respectively. In these tables the values of material constants of polyethylene without nanoparticles are also shown. It should be noted that the films with Fe or CdS nanoparticles as well as corresponding films of polyethylene without nanoparticles have been mould at different temperatures. For the films with Fe and CdS nanoparticles the mould temperatures were 300^0C and 110^0C, respectively.

Fe, %	ρ, kg/m^3	C_{11}×10^8, Pa	η_{11}, Pa×s	C_{66}×10^8 Pa	η_{66}, Pa×s
0	879.5	16	24	1.4	2.9
2	884.1	23.2	24.6	2.6	2.2
5	918.6	20.1	6.2	2.8	2.3
7	972.6	17.8	4	3.4	2.4
12	993.7	15.1	7.6	3.5	1.1
15	991.3	14	4	3.4	0.7
17	986.6	12.8	11.3	3	1.3
20	1052	13.3	22.8	3.5	5.8
25	1186	21.1	19.8	3	0.3

Table 1 The parameters of nanocomposite film containing Fe nanoparticles

CdS, %	ρ, kg/m^3	C_{11}×10^8, Pa	η_{11}, Pa×s	C_{66}×10^8 Pa	η_{66}, Pa×s
0	1001	30	45.1	0.7	0.4
5	1142	41	40.2	1.1	2.9
10	1157	38	19.3	2.4	1.7
30	1277	27	20	1.9	1.5

Table 2 The parameters of nanocomposite film containing CdS nanoparticles

3 Theoretical results

As a result of conducted calculation the velocity and attenuation per wavelength have been found for SH_0 wave propagating in structure "piezoelectric plate – nanocomposite polymeric film". Figs. 2 – 3 show the dependencies of velocity and attenuation of SH_0 wave on ratio d/h for different values of concentration of Fe or CdS nanoparticles in polymeric film for hf =500 m/s, and 1500 m/s, respectively. The characteristics of SH_0 wave were calculated for structures "Y-X lithium tantalate plate– nanocomposite polymeric film containing Fe nanoparticles" (Figs. 2a - 3a) and "Y-X lithium niobate plate– nanocomposite polymeric film containing Fe nanoparticles"(Figs. 2b -3b). It has been also calculated the similar dependencies for SH_0 wave propagating in structure "Y-X lithium tantalate plate– nanocomposite polymeric film containing CdS nanoparticles" (Figs. 4a - 5a) and "Y-X lithium niobate plate– nanocomposite polymeric film containing CdS nanoparticles"(Figs. 4b -5b).

One can see that for the certain values of the ratio of thicknesses of plate and film there are exists the resonant attenuation of acoustic wave. This can be explained by the following. If one side of the film is mechanically free and the second one is mechanically fixed such film can resound in the case when its thickness is equal nλ/4 [5] (λ = wavelength, n = odd number). This corresponds to our case because the mechanical impedance of plate is significantly more than film impedance and in the plane x_3=0 the film may be considered as fixed. For example, analysis showed that for given frequency 1.59 MHz the resonant attenuation of SH_0 wave in structure "Y-X lithium niobate plate – nanocomposite film with Fe 7%" occurs at the film thickness 94 micron. This is equal to λ/4 because the wavelength is 377 micron at the value of velocity 591 m/s. It should be noted that resonant value of film thickness does not depend on the plate thickness and plate material. As for the velocity of waves under study, its dependence on ratio d/h near the resonant value of thickness correlates with the analogous behavior of the phase of oscillation of resonator near the resonant frequency. One can also see that the resonant value of attenuation for lithium niobate plate is significantly more than for lithium tantalate plate. This may be explained by the fact that the velocity of SH_0 wave in lithium niobate plate is more than one in lithium tantalate plate. Therefore the angle between wave vectors of bulk acoustic wave (BAW) in film and SH_0 wave in lithium niobate plate is closer to 90^0 in comparison with lithium tantalate plate. This leads to more value of Q factor for lithium niobate plate and respectively to more value of attenuation. Here one can see the analogy with the RF resonator, which is connected with RF wave-guide as one-terminal device.

The obtained results allow choosing such values of ratio d/h for which the acoustic wave does not practically attenuate in the presence of the film. This opens the prospects of development of undisturbed substrates of nanocomposite materials for thin piezoelectric plates.

Such structures may be useful for development of various thermostable chemical and biological sensors and signal processing devices. Moreover our results show the possibility of exact measuring the phase velocity of BAW in nanocomposite polymeric films.

5 Conclusion

We have investigated the influence of nanocomposite polymeric films containing Fe or CdS nanoparticles of various concentrations on characteristics of SH_0 acoustic waves propagating in thin piezoelectric plates. The conducted analysis has showed that for value of film

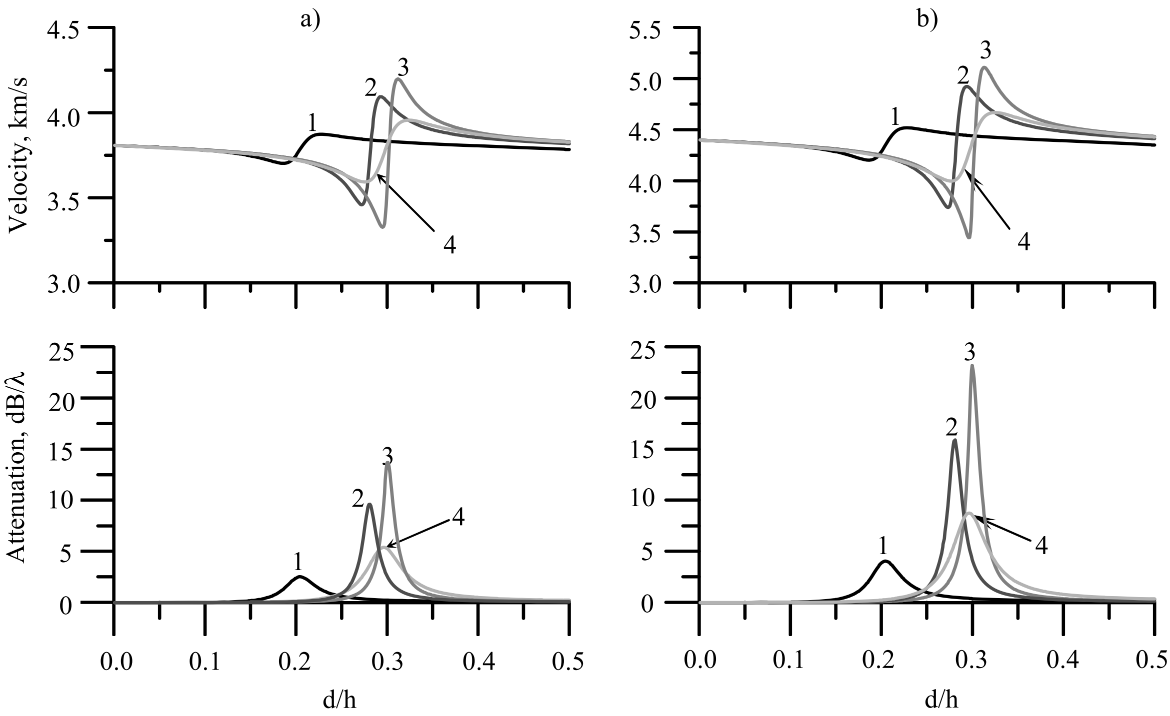

Fig.2 Velocity and attenuation per wavelength versus d/h for SH_0 wave in YX $LiTaO_3$ (a) and YX $LiNbO_3$ (b) plates contacted with nanocomposite polymeric film containing 0% (1), 5% (2), 7% (3), and 20% (4) of Fe nanoparticles at parameter hf=500 m/s, f=1.59 MHz.

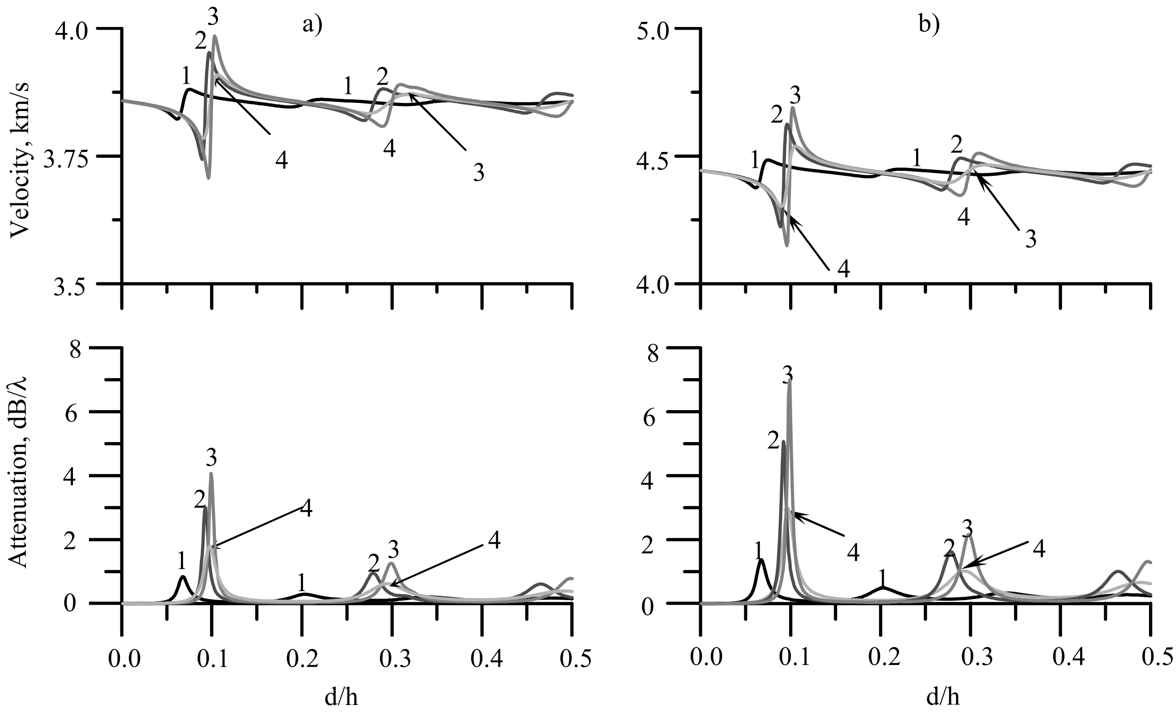

Fig.3 Velocity and attenuation per wavelength versus d/h for SH_0 wave in YX $LiTaO_3$ (a) and YX $LiNbO_3$ (b) plates contacted with nanocomposite polymeric film containing 0% (1), 5% (2), 7% (3), and 20% (4) of Fe nanoparticles at parameter hf=1500 m/s, f=1.59 MHz

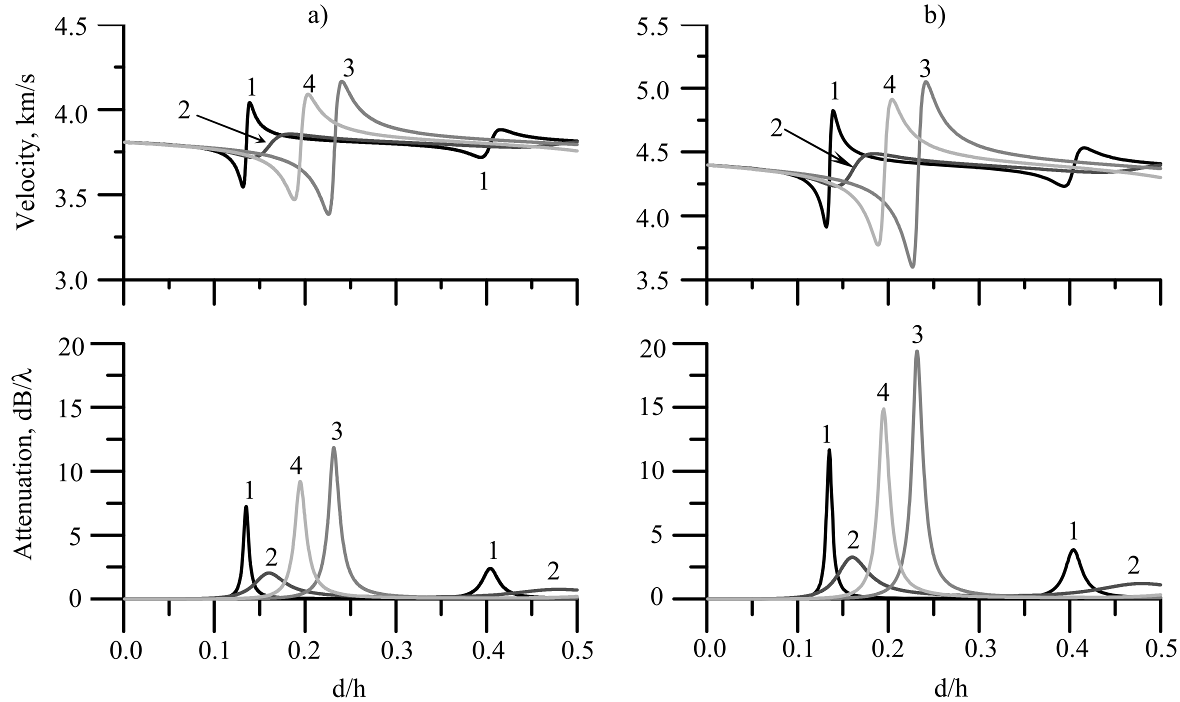

Fig.4 Velocity and attenuation per wavelength versus d/h for SH_0 wave in YX $LiTaO_3$ (a) and YX $LiNbO_3$ (b) plates contacted with nanocomposite polymeric film containing 0% (1), 5% (2), 10% (3), and 30% (4) of CdS nanoparticles at parameter hf=500 m/s, f=1.59 MHz.

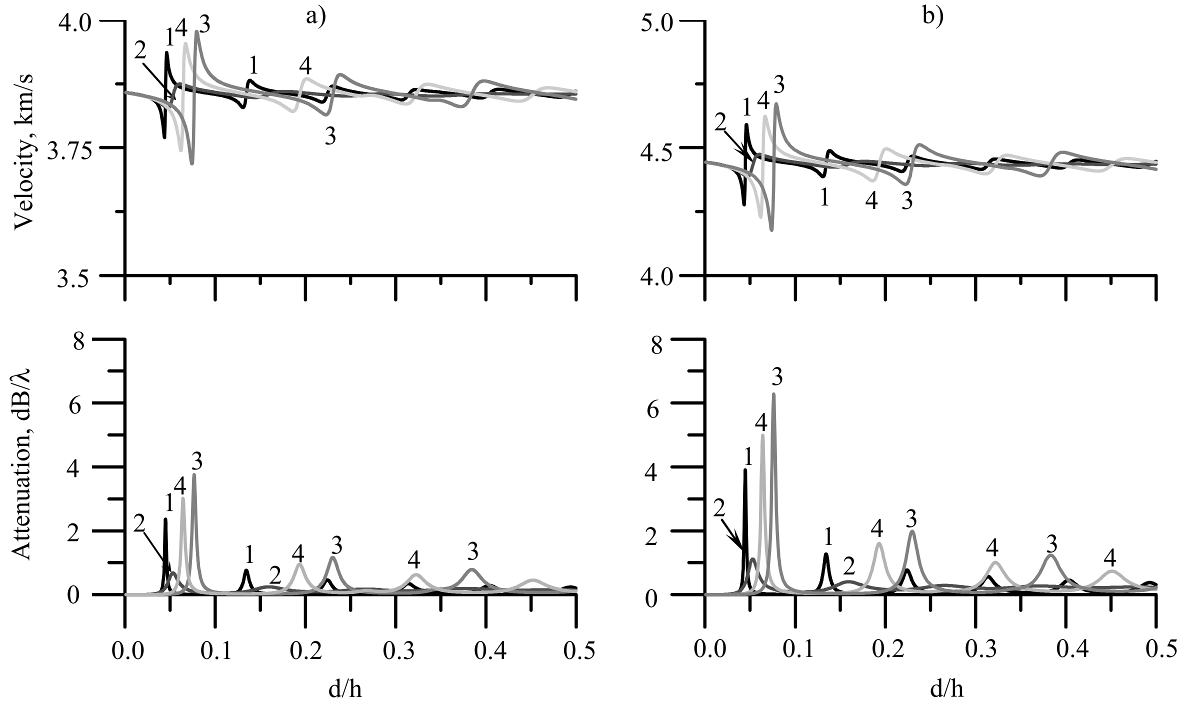

Fig.5 Velocity and attenuation per wavelength versus d/h for SH_0 wave in YX $LiTaO_3$ (a) and YX $LiNbO_3$ (b) plates contacted with nanocomposite polymeric film containing 0% (1), 5% (2), 10% (3), and 30% (4) of CdS nanoparticles at parameter hf=1500 m/s, f=1.59 MHz.

thickness $n\lambda/4$ (n = odd number) the attenuation of investigated wave has the resonant behavior. At that the resonant thickness for fixed value of the frequency does not depend on plate thickness and plate material. As for the velocity of waves under study, its dependence on ratio d/h near the resonant value of thickness correlates with the analogous behavior of the phase of oscillation of resonator near the resonant frequency. It has been shown and explained that the resonant value of attenuation for lithium niobate plate is significantly more than for lithium tantalate plate.

The obtained results allow choose such values of ratio d/h for which the acoustic wave does not practically attenuate in the presence of the film. This opens the prospects of development of undisturbed substrates of nanocomposite materials for thin piezoelectric plates. Such structures may be useful for development of various thermostable chemical and biological sensors and signal processing devices. Moreover our results show the possibility of exact measuring the phase velocity of BAW in nanocomposite polymeric films.

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