The influence of the adhesive bonding on the magnetoelectric effect in bilayer magnetostrictive-piezoelectric structure

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Abstract. The influence of the interlayer adhesive bonding is considered in bilayer magnetostrictive-piezoelectric structure. The expression for the frequency dependence of the magnetoelectric voltage coefficient in the electromechanical resonance region is obtained using the simultaneous solution of the motion equations for the magnetostrictive, adhesive, piezoelectric phases and material equations. It is shown that in the passage to the limits this expression for the coefficient transforms to the expression for ideal connection between the layers.

1. Introduction
Ferrite-piezoelectric structures excite great interest, because in these structures there are effects which can be absent in ferrite and piezoelectric components separately. These effects appear due to mechanical interaction between the magnetostrictive and piezoelectric subsystems. One of such effects is the magnetoelectric (ME) effect, which is the change of the electric polarization under applied magnetic field: so called linear ME effect, or the occurrence of magnetization under applied electric field (inverse ME effect). The advantage of bilayer ferrite-piezoelectric structures is that the value of ME effect in such samples is greater than in bulk composites, thereby they are of great interest for the creation of various devices based on solid-state electronics. The ME effect is caused by the elastic interaction of magnetostrictive and piezoelectric subsystems in bilayer structures. The applied magnetic field induces mechanical deformations in the magnetostrictive phase which pass via mechanical coupling into the piezoelectric phase and lead to the change of the polarization of the sample. The frequency dependence of the effect is defined by the dispersion relation for such type of waves, because the ME effect in composites is caused by the elastic interaction of magnetostrictive and piezoelectric phases. Magnetostrictive-piezoelectric bilayer structures offer certain advantages over bulk composites [1], because they can be polarized much easier and exhibit practically no leakage currents as the magnetostrictive phase is insulated by the high-resistivity piezoelectric layer. The theory of the ME effect in bulk and multilayer composites based on the effective parameters method at the low frequency region was presented in works [2-6] and in the region of electromechanical resonance was first developed in works [7-9]. But the method of effective parameters can be used when the characteristic size of the structure units of the composite is much smaller than the acoustic wavelength and in this case the composite can be regarded as a homogeneous medium. Consideration of the magnetoelectric effect in layered structures based on the simultaneous solution of the equations of motion and constitutive relations for the magnetostrictive and piezoelectric phases was previously presented in [10-16]. Therein, an expression for ME voltage coefficient was derived based on the simultaneous solution of motion and material equations for the magnetostrictive and piezoelectric phases taking into account the boundary conditions on the interface. Thus, the consideration of the interlayer adhesive bonding was taken into account formally by an interface coupling coefficient in [10-12] or by an assumption of ideal coupling and equal oscillation amplitude over the thickness of both magnetostrictive and piezoelectric phases [13]. The ME effect in bilayer magnetostrictive-piezoelectric structure was presented in case of a perfect bonding taking into account the changes of the amplitude in oscillations over the thickness of the sample [14-16]. Recently the ME effect was
investigated in laminated composite structure coupled by a bonding material considering the interlayer bonding material in work [17]. But in this work the amplitude change of the oscillations over the thickness of the sample (in direction perpendicular to the interface) was not assumed. In this work, the parameters of the adhesive bonding material and the amplitude change of the oscillations over the thickness are taken into account. Using motion equation, elastodynamics and electrostatic equations for the magnetostrictive piezoelectric phases and taking into account the boundary conditions on the interface, the equation for frequency dependence of the ME effect was obtained. It is shown that the value of the effect depends not only on parameters of magnetostrictive and piezoelectric phases, but also the parameters of interlayer adhesive material. For the case of ideal coupling this equation transforms to the equation previously obtained.

2. Model
As a model, we consider a bilayer structure in the form of a rectangular plate of length \( L \) and width \( W \), consisting of mechanically interacting magnetostrictive, adhesive and piezoelectric layers of thickness \( t_m \), \( t_G \) and \( t_p \) respectively, the values which are not assumed to be small. Thin metal contacts are applied on the top and the bottom of the plate. The direction of the wave propagation \( X \) coincides with the interface of the piezoelectric and adhesive layers. The direction \( Z \) is perpendicular to that interface as it is shown in figure 1. Preliminarily, the piezoelectric layer is polarized perpendicularly to the contacts (\( Z \) axis). Let us consider the longitudinal ME effect. In this case, the magnetic field coincides with the direction of polarization.

![Figure 1 Schematic view of the sample](Image)

1 - Magnetostrictive phase, 2 - Piezoelectric phase, 3 - Adhesive phase, 4 - Electrodes.

The alternating magnetic field with angular frequency \( \omega \) causes elastic oscillations in the magnetostrictive components, transferring through the interface of the partition to the piezoelectric component through the shear stresses, which brings to interconnected oscillations of magnetostrictive and piezoelectric subsystems. As there is a nonuniformity along \( Z \) axis and the width of the plate \( W \) (\( Y \) axis) is small, under the first approximation we can assume that the displacements along plane \( Y \) are homogeneous and the nonzero components of stress are only \( \alpha T_{xx} \) and \( \alpha T_{xz} \). The value of the stresses will depend on the thickness of the sample, perpendicularly to the interface between magnetostrictive and piezoelectric phases. Therefore the equations of motion for the \( x \) projection of the \( \alpha u_x \) displacement vector for the magnetostrictive, adhesive and piezoelectric phases are of the form

\[
\alpha \rho \frac{\partial^2 \alpha u_x}{\partial t^2} = \frac{\partial \alpha T_{xx}}{\partial x} + \frac{\partial \alpha T_{xz}}{\partial z},
\]  

(1)
where upper-case index “α” is correspondingly “m” for ferrite, “G” for glue and “p” for piezoelectric; $\alpha \rho$ is the density of ferrite, adhesive and piezoelectric layers; $\alpha T_{ij}$ are the components of the stress tensor. The constitutive equations for the magnetostrictive, adhesive and piezoelectric phases are

$$\begin{align*}
    mS_{xx} &= \frac{1}{mY} mT_{xx} + m q_{xx,z} m H_z, \\
    mS_{xz} &= \frac{1}{mG} mT_{xz}, \\
    G S_{xx} &= \frac{1}{G Y} G T_{xx}, \\
    G S_{xz} &= \frac{1}{G G} G T_{xz}, \\
    p S_{xx} &= \frac{1}{pY} pT_{xx} + p d_{xx,z} p E_z, \\
    p S_{xz} &= \frac{1}{pG} p T_{xz}, \\
    p D_z &= p E_z, p T_{xz}.
\end{align*}$$

where $\alpha S_{ij}$ are the strain tensor of the magnetostrictive, adhesive and piezoelectric phases; $\alpha E_z$ and $m H_z$ are the electric and magnetic fields; $\alpha D_z$ is the electric displacement; $\alpha Y$ and $\alpha G$ are the Young’s modulus and shear modulus; $\alpha d_{xx,z}$ and $m q_{xx,z}$ are the piezoelectric and piezomagnetic coefficients; $\alpha E_{zz}$ is the tensor component of permittivity.

Taking into account the nonuniformity along $Z$ axis, the solution of equation for the displacement vector will be presented as planar waves, whose amplitudes are changed on the thickness of the sample and have the following form:

$$\alpha u(x, z) = \alpha g(z) (\alpha A \cos(\alpha x - kx) + \alpha B \sin(\alpha x - kx)),$$

where $\alpha A$ and $\alpha B$ are the constants of integration and $\alpha g(z)$ are some functions.

The substitution of (9) into the expression for the motion of the medium gives the equation for function $\alpha g(z)$. Solution of this equation depends on the elastic wave velocity in ferrite, piezoelectric and adhesive phases. For the sake of definiteness, we choose a structure of ferrite, piezoelectric and adhesive, in which the velocity of elastic waves in the ferrite will be higher than that in the piezoelectric and adhesive phases. The boundary conditions, namely, the normal components of stress tensor on top and bottom surfaces are zero. The displacement and the shear stresses are equal on the ferrite-adhesive and adhesive-piezoelectric interfaces. These boundary conditions determine a system of equations. Solution of these equations gives the dispersion relation in the following form:

$$\begin{align*}
    m Y^m \alpha th(m \kappa) \left(1 - \operatorname{tg}(G \kappa) \operatorname{tg}(P \kappa) \frac{p Y p \kappa}{G Y G \kappa} \right) =
    p Y^p \alpha g(p \kappa) \left(1 + \frac{\operatorname{tg}(G \kappa)}{\operatorname{tg}(P \kappa)} \frac{G Y G \kappa}{p Y p \kappa} \right),
\end{align*}$$

where $\kappa$ is a wave vector.
where \( \alpha, \beta \) are non-dimensional parameters,

\[
m^2 \chi^2 = -2(1 + \nu) \left[ \frac{\omega^2}{\alpha V_L^2} - k^2 \right], \quad \rho^2 \chi^2 = 2(1 + \nu) \left[ \frac{\omega^2}{\rho V_L^2} - k^2 \right], \quad \alpha V_L^2 = \frac{\alpha \beta}{\alpha_y}.
\]

\( \alpha V_L \) are the velocities of longitudinal waves respectively in the magnetostrictive, piezoelectric and adhesive medium, and \( \nu \) is the Poisson’s ratio.

Equation (10) defines the dependence of angular frequency \( \omega \) from the wave number \( k \) in an implicit form for the propagation of elastic waves in bilayer magnetostrictive-piezoelectric structures taking into account the adhesive phase. As we can see this equation transforms to the equation previously obtained for the case of ideal contact [14-16].

### 3. The ME voltage coefficient

Magnetoelastic voltage coefficient is defined as the ratio of the average value of the electric field to the average value of the external magnetic field, which induced it, i.e.:

\[
< \alpha_E > \equiv \frac{< E >}{< H >},
\]

where \( < E > \equiv \frac{U}{(m^2 + \rho^2 + \eta)} \) is the average value of the electric field of the structure. With this method of determination, the ME voltage coefficient characterizes the efficiency of ME transformation of the entire structure. In order to define a theoretical expression for the ME voltage coefficient, we use the method developed earlier [15,16]. The condition of mechanical equilibrium at the free surfaces of the plate, i.e. points \( x = \pm \frac{L}{2} \), gives boundary conditions in the form

\[
\int_{-\frac{L}{2}}^{0} \rho T_{xx}(\pm \frac{L}{2}, z) dz + \int_{0}^{\alpha_t} G T_{xx}(\pm \frac{L}{2}, z) dz + \int_{\alpha_t}^{\alpha_t + \alpha_f} \rho T_{xx}(\pm \frac{L}{2}, z) dz = 0.
\] (12)

Using (12) we can calculate the constants of integration \( A \) and \( B \) in (9). We will find the ME voltage coefficient using the open circuit condition \( I = 0 \), where the electric current is determined by the expression

\[
I = \frac{\partial}{\partial t} \int_{-\frac{L}{2}}^{\frac{L}{2}} \rho D_z dz.
\] (13)

Expressing the stress tensor component \( \rho T_{xx} \) by the strain tensor component \( \rho S_{xx} \) from (6) and substituting it into (8), we obtain expression for the electric displacement \( \rho D_z \). Then, substituting the expression obtained for \( \rho D_z \) into (13) and using the condition of open circuit \( I = 0 \), we obtain the equation for the electric field \( < E > \) taking into account (9) and (12). Thus, we find the ME voltage coefficient using (11) and the fact that the potential difference between the electrodes is defined as \( U = < E > \rho D_z \). Finally, in the case of longitudinal orientation of the fields, we obtain the expression for the ME voltage coefficient in the form:

\[
\alpha_E = \frac{\rho Y \rho T_{xx} \frac{m^2 \chi^2}{\alpha_v \chi}}{\rho \alpha_{vz} \Delta_k} \quad \frac{\rho^2 \chi^2}{\Delta_k} \quad \frac{\rho \alpha_{v \chi}}{\rho Y \frac{\rho T_{xx}}{\rho Y \chi}} \quad \frac{\rho \alpha_{v \chi}}{\rho Y \frac{\rho T_{xx}}{\rho Y \chi}} \quad \rho \lambda
\]

where \( \Delta_k = \cos(G \chi) \left[ 1 - \frac{\rho \chi}{\rho Y \chi} \right] \frac{\rho Y \rho T_{xx}}{\rho Y \chi}, \quad C_Y = 1 - \frac{\rho \chi}{\rho Y \chi} \left[ \frac{\rho Y \rho T_{xx}}{\rho Y \chi} \right] \frac{\rho Y \rho T_{xx}}{\rho Y \chi} \).
and
\[ \Delta_a = 1 - K_p^2 \left( 1 - \frac{p Y \eta}{m \kappa} \frac{\tanh(m \kappa)}{\cosh(m \kappa)} \cdot \frac{\tan(\kappa)}{\kappa} \right) \]

with
\[ K_p^2 = \frac{p Y (p d_{xx})^2}{p E_{zz}} \]

the squared coefficient of electromechanical coupling and \( \kappa = kL/2 \) the dimensionless parameter.

As follows from (14), the frequency dependence of the ME voltage coefficient has resonant character in bilayer magnetostrictive-piezoelectric structures considering the adhesive phase. At the so-called antiresonance frequencies when \( \Delta_a = 0 \), there is a peak increase in the ME voltage coefficient. It can also be seen that the value of ME voltage coefficient depends on each, parameters of magnetostrictive, adhesive and piezoelectric phases and the length of the structure.

In the low frequency region, the magnetoelastic voltage coefficient is nearly independent of frequency. Expanding Eq. (14) in powers of the small parameters \( m \kappa \), \( G \kappa \), \( p \kappa \) and retaining only the first-order terms of the expansion, we find the low-frequency value of the coefficient

\[ \alpha_{low} = \frac{p Y d_{xx} m q_{zz}}{p E_{zz}} \left( 1 - K_p^2 \left( 1 - \frac{p Y \eta}{m \kappa} \frac{\tanh(m \kappa)}{\cosh(m \kappa)} \cdot \frac{\tan(\kappa)}{\kappa} \right) \right) \]

As we can see from (15), the value of the ME voltage coefficient decreases by the increase of the thickness of the adhesive layer.

4. Conclusion
The consideration of the adhesive bonding leads to a change of the results for the value of the ME voltage coefficient in a bilayer magnetostrictive-piezoelectric structure. It also leads to the nonlinear dispersion relation between the angular frequency and the wave number. The derived relations in the limiting case, when the thickness of the adhesive layer tends to zero, transform to the relations derived earlier for the case of ideal contact. The value of the ME voltage coefficient decreases with the increase of the thickness of the adhesive layer.

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