Strength of multiferroic layered structures in position sensor structures

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Abstract. The article is devoted to modeling and calculating the strength of multiferroic layered structures in the designs of position sensors used in various practical applications, including CPS sensors. Progress in the study of new multiferroic layered structures in which a giant magnetoelectric (ME) effect has been discovered has opened up completely new prospects for the design of position sensors. The studies carried out open up obvious prospects for creating economical and cheap sensors for use in CPS structures, as well as electric motors for determining angular positions and other automated systems. The strength test of magnetostrictive-piezoelectric two-layer structures metglas/PZT, metglas/(LiNbO3 cut Y+140°), metglas/GaAs was carried out in the bending mode of the magnetoelectric effect. It was found that in all cases the strength condition is satisfied with a very good margin. Thus, the reliability of position sensors with a magnetoelectric structure is fully ensured. The studies carried out open up obvious prospects for creating economical and cheap sensors for use in CPS structures, as well as electric motors for determining angular positions and other automated systems.

1. Introduction
Position sensors are one of the main components used in automation devices and for the automation of various technological processes. Position sensors are widely used in the automotive industry as crankshaft position sensors (CPS). For the designs of CPS sensors, inductors on a metal magnetic core and Hall sensors in a miniature design are most often used [1]. Progress in the study of new multiferroic layered structures in which the giant magnetoelectric (ME) effect was discovered [2] has opened up completely new prospects for the design of position sensors [3]. The studies carried out open up obvious prospects for creating economical and cheap sensors for use in CPS structures, as well as electric motors for determining angular positions [4] and other automated systems. New materials such as self-biased magnetoelastic structure have opened up unique possibilities for improving automotive sensors [5].

For use in technical devices, strong and reliable materials are required. In addition to direct strength tests, methods of modeling and predicting the conditions of destruction of the objects under study are widespread. A clear advantage of the modeling method is its low cost and speed of obtaining results.
The requirements for sensors that are used in cars are of a very high level, as it relates to human safety. Sensors are subjected to various types of mechanical stress, they operate in a wide temperature range, in addition, there are effects of electric and magnetic fields. The reliability of such a sensor should provide a continuous vehicle range of hundreds of thousands of kilometers. Thus, preliminary verification of the ME structure for strength is an urgent problem.

Various materials are used to manufacture multiferroic layered structures with magnetoelectric effect [6]. For example, composite structures based on PZT piezoelectric ceramics and magnetostrictive materials such as nickel or metglas alloy are used. Layered multiferroic structures based on monocrystalline substances and magnetostrictive metals or alloys, including such as Terfenol-D. Multiferroic means that in these materials several types of “ferro” ordering coexist simultaneously: ferromagnetic and ferroelectric. For research we have chosen the following materials PZT, LiNbO$_3$, GaAs, metglas. By connecting the magnetostrictive component and the piezoelectric component, the required multiferroic medium is obtained.

The purpose of the article is to calculate the strength of multiferroic layered structures in the designs of position sensors in order to understand the limits of the operation of these sensors.

2. Modeling and strength analysis

For calculation and modeling, the theoretical approach for calculating the ME of composites is used, given in [7]. Information from articles [8-10] was used as the initial data. The parameters of the piezoelectric composite were taken from the website of OOO Avrora-ELMA.

The most severe operating conditions occur in the resonant mode. The strength test of magnetostrictive-piezoelectric two-layer structures metglas/PZT, metglas/(LiNbO$_3$ cut Y + 140°), metglas/GaAs in the bending mode of resonance of the magnetoelectric effect is carried out below.

Total composite thickness

$$t = p_t + m_t. \quad (1)$$

Volume fractions of piezoelectric and ferromagnet

$$p_v = \frac{p_t}{t}, \quad m_v = \frac{m_t}{t}. \quad (2)$$

Effective density of the composite

$$\rho = p_v \rho_p + m_v \rho_m. \quad (3)$$

We draw the axis $X$ along the neutral line of the composite beam:

\[ \text{Figure 1. The position of the interface between the piezoelectric and magnetostrictive phases relative to the neutral line in a two-layer composite.} \]

Longitudinal component of the strain tensor

$$S_1 = -2 \frac{\partial^2 w}{\partial x^2}. \quad (4)$$
where \( w \) is the lateral displacement.

Longitudinal component of the stress tensor in a piezoelectric

\[
\mathbf{T}_1 = c_{44}^{D_1} S_1 - \bar{h}_{31} D_3 ,
\]

(5)

the third component of the electric field strength vector

\[
E_3 = -\bar{h}_{31} S_1 + \bar{p}_{33}^D D_3 ,
\]

(6)

where

\[
\bar{c}_{11}^D = \left( \frac{\rho S_{11} - \frac{d^2}{3}}{e_{33}^E e_0} \right)^{-1},
\]

\[
\bar{h}_{31} = \tau_{11}^0 d_{31} ,
\]

\[
\bar{p}_{33}^D = \frac{1 + \bar{h}_{31} d_{31}}{e_{33}^E e_0} .
\]

(7)

Longitudinal component of the stress tensor of metglass

\[
m_T_1 = \frac{m_Y B}{1 - m_Y^2} \left( S_1 - q_{11} h_1 \right) ,
\]

(8)

where \( \frac{m_Y B}{1 - m_Y^2} \) and \( m_Y^2 \) are the magneto-mechanical coupling coefficient and the square of the magneto-mechanical coupling coefficient.

We substitute (4) into (8) and get

\[
m_T_1 = -z q_{11} \frac{\partial^2 w}{\partial x^2} - \bar{g}_{11} h_1 ,
\]

(9)

where \( q_{11} = \frac{m_Y B}{1 - m_Y^2} q_{11} \).

Torque

\[
M = \int_{z_0}^{z_0 + m t} b z \mathbf{T}_1 dz + \int_{z_0}^{z_0 + m t} b m_T_1 dz = -b \frac{\partial^2 w}{\partial x^2} D - \int \frac{\partial^2 w}{\partial x^2} D_3 - \int b^m t^2 \langle q_{11} \rangle h_1 ,
\]

(10)

where

\[
\langle h_{31} \rangle = \frac{1}{m t^2} \int_{z_0}^{z_0 + m t} \bar{h}_{31} dz = \frac{2z_0 - x_{0+}^t \bar{h}_{31}}{2^t},
\]

\[
\langle q_{11} \rangle = \frac{1}{m t^2} \int_{z_0}^{z_0 + m t} \bar{q}_{11} dz = \frac{\bar{q}_{11} \left( 2z_0 + m t \right)}{2^t} ,\]

(11)

total cylindrical stiffness of the composite beam

\[
D = \rho D + m D ,
\]

(12)

where

\[
\rho D = \frac{1}{3} \bar{c}_{11}^D \rho t \left( \frac{\rho t^2}{3} - 3 \rho t z_0 + 3 z_0^2 \right) ,
\]

\[
m D = \frac{1}{3} \frac{m_Y B m t}{1 - m_Y^2} \left( \frac{m t^2}{3} + 3 m t z_0 + 3 z_0^2 \right) ,
\]

(13)

\( b \) – the width of the magnetoelectric composite.

Let us find the voltage across the piezoelectric
\[ U = \int_{z_0}^{z_f} E_s dz = \frac{p}{t^2} \langle h_{11} \rangle \frac{\partial^2 W}{\partial x^2} + \frac{p}{t} \langle \beta_{33}^S \rangle D_3, \]  

where

\[ \langle \beta_{33}^S \rangle = \frac{1}{p t} \int_{z_0}^{z_f} \bar{\beta}_{33}^s dz = \bar{\beta}_{33}^S. \]  

Hence, we express the electrical displacement in the piezoelectric

\[ D_3 = \frac{U}{p t \langle \beta_{33}^S \rangle} - \frac{p t \langle h_{11} \rangle}{\langle \beta_{33}^S \rangle} \frac{\partial^2 W}{\partial x^2} \]  

and substitute in (10)

\[ M = -b t^3 \langle c_{11} \rangle \frac{\partial^2 W}{\partial x^2} - \frac{b p t \langle h_{11} \rangle}{\langle \beta_{33}^S \rangle} U - b^m n t \langle q_{11} \rangle h_i, \]  

where

\[ \langle c_{11} \rangle = \frac{1}{t^2} \left( D - \frac{p t^3 \langle h_{11} \rangle^2}{\langle \beta_{33}^S \rangle} \right). \]  

The position of the interface between the piezoelectric and magnetostrictive phases relative to the neutral line \( z_0 \) is determined from the minimum condition \( \langle c_{11} \rangle \)

\[ z_o = \frac{(e_{11}^p t^2 - m_y n^m t^2)(\beta_{33}^S) - h_{33}^2 p t^2}{2(m_y n^m t + e_{11}^p t)(\beta_{33}^S) - 2 h_{33}^2 p t}. \]  

Transverse force

\[ V = \frac{\partial M}{\partial x} = -b t^3 \langle c_{11} \rangle \frac{\partial^3 W}{\partial x^3}. \]  

Bending vibration equation

\[ \rho b t \frac{\partial^4 w}{\partial \tau^4} = \frac{\partial V}{\partial x}. \]  

Substituting (20) into (21), we obtain

\[ t^2 \langle c_{11} \rangle \frac{\partial^4 w}{\partial x^4} + \rho \frac{\partial^3 w}{\partial \tau^3} + \rho \frac{\partial w}{\partial x} = 0. \]  

Time shift is harmonic \( w \sim e^{i\omega \tau} \), therefore

\[ \frac{\partial^4 w}{\partial x^4} - k^4 w = 0, \]  

where the wavenumber

\[ k = \left( \frac{\rho}{t^2 \langle c_{11} \rangle \omega^2} \right)^{1/2}. \]
General solution of the equation of motion (23)

\[ w = C_1 \cosh(kx) + C_2 \sinh(kx) + C_3 \cos(kx) + C_4 \sin(kx). \]  

(25)

Open circuit condition

\[ \int_0^l D_2 dx = 0 \]  

(26)

We integrate (14) over \( x \)

\[ Ul = \int \rho t^2 \left\langle h_{31} \right\rangle \frac{\partial w}{\partial x} \bigg|_0^l = \rho t^2 \left\langle h_{31} \right\rangle k \left[ C_1 r_2 + C_2 (r_1 - 1) - C_3 r_4 + C_4 (r_5 - 1) \right], \]  

(27)

where

\[ r_1 = \cosh(kl) \]

\[ r_2 = \sinh(kl) \]

\[ r_3 = \cos(kl) \]

\[ r_4 = \sin(kl) \]  

(28)

Boundary conditions for rigidly restrained one end of the beam and free fixing of the other end of the beam

\[ w(0) = 0 \]

\[ \frac{\partial w}{\partial x}(0) = 0 \]

\[ V(l) = 0 \]

\[ M(l) = 0 \]  

(29)

Combining boundary conditions (29) with (27), we obtain a linear system of five inhomogeneous algebraic equations with respect to five unknowns \( C_1, C_2, C_3, C_4, U \)

\[ C_1 + C_3 = 0 \]

\[ C_2 + C_4 = 0 \]

\[ C_1 r_2 + C_2 r_1 + C_3 r_4 - C_4 r_3 = 0 \]

\[ -t^3 \left\langle c_{11} \right\rangle k^2 \left( C_1 r_1 + C_2 r_2 - C_3 r_3 - C_4 r_4 \right) - \rho t^2 \left\langle h_{31} \right\rangle U - \rho t^2 \left\langle q_{11} \right\rangle h_{31} = 0 \]

\[ Ul = \rho t^2 \left\langle h_{31} \right\rangle k \left[ C_1 r_2 + C_2 (r_1 - 1) - C_3 r_4 + C_4 (r_5 - 1) \right] \]  

Taking into account that \( r_1^2 - r_2^2 = 1, r_3^2 + r_4^2 = 1 \), we will find a solution for this system.
\[ C_1 = -C_3 = -\frac{l^m t^2 \langle q_{11} \rangle \langle \beta_{33}^S \rangle (r_1 + r_3)}{2k \left( \langle c_{11} \rangle klt^3 \langle \beta_{33}^S \rangle (1 + r_1 r_3) + \rho t^3 \langle h_{31} \rangle^2 (r_1 r_4 + r_2 r_3) \right)} h_i \]

\[ C_2 = -C_4 = -\frac{l^m t^2 \langle q_{11} \rangle \langle \beta_{33}^S \rangle (r_2 - r_4)}{2k \left( \langle c_{11} \rangle klt^3 \langle \beta_{33}^S \rangle (1 + r_1 r_3) + \rho t^3 \langle h_{31} \rangle^2 (r_1 r_4 + r_2 r_3) \right)} h_i. \]  

(31)

\[ U = -\frac{m t^2 \rho t^2 \langle q_{11} \rangle \langle h_{31} \rangle \langle \beta_{33}^S \rangle (r_1 r_4 + r_2 r_3)}{\langle c_{11} \rangle klt^3 \langle \beta_{33}^S \rangle (1 + r_1 r_3) + \rho t^3 \langle h_{31} \rangle^2 (r_1 r_4 + r_2 r_3)} h_i \]

Then the ME-coefficient for voltage

\[ \alpha_x = \frac{E_x}{h_i} = -\frac{m t^2 \rho t^2 \langle q_{11} \rangle \langle h_{31} \rangle \langle \beta_{33}^S \rangle (r_1 r_4 + r_2 r_3)}{klt^3 \langle \beta_{33}^S \rangle (1 + r_1 r_3) + \rho t^3 \langle h_{31} \rangle^2 (r_1 r_4 + r_2 r_3)}. \]

(32)

To account for losses in the calculation, you need to put \( \omega = 2\pi \left( 1 + \frac{1}{2Q} \right) f \), where the quality factor of the resonance is \( Q = 51 \).

Figure 2 shows the dependence of the magnetoelectric voltage coefficient on the frequency of the alternating magnetic field.

**Figure 2.** Dependence of the magnetoelectric voltage coefficient on the frequency of the alternating magnetic field.

The calculation used the following material parameters of metglass 2605S3A: \( m\rho = 7290 \frac{kg}{m^3} \), \( mY = 1.0 \cdot 10^{11} \) Pa, \( \mu = 10^4 \), \( q_{11} = 3.5 \cdot 10^{-9} \frac{m}{A} \), thickness \( m t = 6.9 \cdot 10^{-5} \) m; material parameters PZT: \( p\rho = 7510 \frac{kg}{m^3} \), \( p_{s11} = 1.53 \cdot 10^{-11} \frac{m^2}{N} \), \( e_{33}^T = 1750 \), \( d_{31} = -1.75 \cdot 10^{-10} \frac{m}{V} \), thickness \( p_t = 5 \cdot 10^{-4} \) m; length of magnetoelectric sample \( l = 2.5 \cdot 10^{-2} \) m.

Resonance frequency for the flexural mode of the magnetoelectric effect in such a sample \( f_r = 485.6 \) Hz.

Limiting voltage for PZT \( \sigma_m = 80 \) MPa.

It is obvious that the maximum longitudinal stresses in PZT will occur at the resonant frequency.
Let us find an expression for the longitudinal voltage in a piezoelectric. For this, in (5) we substitute (4) and (16)

\[ p_{T1} = \left( \frac{p_t \tilde{h}_{31}(\tilde{h}_{31})}{\beta_{33}^2} - z \hat{c}_{11} \right) \frac{\partial^2 w}{\partial x^2} - \frac{\tilde{h}_{31} U}{t \beta_{33}^2} \]  

(33)

We have already found the voltage across the piezoelectric \( U \). Let us find the second partial derivative of the vertical displacement along the longitudinal coordinate

\[ \frac{\partial^2 w}{\partial x^2} = k^2 [C_1 \cosh(kx) + C_2 \sinh(kx) - C_3 \cos(kx) - C_4 \sin(kx)] \]  

(34)

Coefficients \( C_1, C_2, C_3, C_4 \) we also already know. Thus, we now also have an expression for the longitudinal stress in PZT.

Obviously, depending on the vertical coordinate \( z \), the longitudinal stress reaches its maximum modulus value either on the lower face of PZT at \( z = z_0 - p_t \), or on the upper face of PZT connected to the metal glass, at \( z = z_0 \).

Figure 3 shows the dependences of the longitudinal stress in PZT on the lower and upper faces on the longitudinal coordinate \( x \). In the calculation, the value of the alternating magnetic field strength was taken \( h_t = 1 \text{ Oe} \).

The figure shows that the longitudinal stress in the PZT reaches its maximum value on the lower edge at \( x = 0 \), that is, at the clamped end. For a given PZT \( p_t = 5 \cdot 10^{-4} \text{ m thickness} \), this maximum value \( p_{T1}^{\text{max}} \).

Let’s do a similar calculation for several PZT thicknesses. The results of this calculation are presented in table 1.

| \( p_t, m \) | \( f_r, Hz \) | \( p_{T1}^{\text{max}}, MPa \) |
|-----------|-------------|-----------------|
| \( 10^{-3} \) | 897.5 | 0.34 |
| \( 5 \cdot 10^{-4} \) | 485.6 | 0.64 |
| \( 3 \cdot 10^{-4} \) | 318.7 | 0.87 |
| \( 10^{-4} \) | 147.5 | 1.24 |
| \( 5 \cdot 10^{-5} \) | 104.0 | 1.14 |
From table 1 we can see that the dependence $T_1^{max}$ on $P_t$ is not too sharp and on the segment $[5 \cdot 10^{-5}, 3 \cdot 10^{-4}]$ has a maximum that cannot greatly exceed 1.24 MPa. Therefore, it is clear that the strength condition is satisfied with a large margin $T_1^{max}$. In the course of the study, mathematical modeling was carried out in an applied engineering package of computer modeling. Figure 4 shows the result of modeling the mechanical stresses in MPa for the ME material metglas/PZT in the flexural mode of resonance for the PZT layer.

![Figure 4](image)

**Figure 4.** Result of simulation of mechanical stresses (VonMises Stress) in MPa for ME material metglas/PZT at flexural resonance mode for PZT layer 0.5 mm thick. The scale shows the value of mechanical stress in the metglas/PZT material in MPa, arrows indicate the value and direction of the force.

Now let's make a similar calculation for a magnetoelectric composite, in which a Y+140 ° cut of lithium niobate is used instead of PZT. Material constants for Y+140 ° cut of lithium niobate:

\[
p \rho = 4647 \, \frac{kg}{m^3}, \quad p_{311}^E = 6.91 \cdot 10^{-12} \, \frac{m^2}{N}, \quad \varepsilon_{33}^E = 49.8, \quad d_{31} = -2.724 \cdot 10^{-11} \, \frac{m}{V}.
\]

According to some data, the limiting stress for Y+140 ° cut of lithium niobate $\sigma_m = 550 \, MPa$, according to other data, it does not exceed the maximum yield stress for lithium niobate 110 MPa.

The results of this calculation are presented in table 2.

| $P_t$, m | $f_\ast$, Hz | $T_1^{max}$, MPa |
|----------|-------------|------------------|
| $10^{-3}$ | 1666.5      | 0.56             |
| $5 \cdot 10^{-4}$ | 844.4 | 1.05             |
| $3 \cdot 10^{-4}$ | 520.5 | 1.59             |
| $10^{-4}$ | 211.7      | 2.86             |
| $5 \cdot 10^{-5}$ | 141.6 | 3.01             |
| $3 \cdot 10^{-5}$ | 114.2 | 2.72             |

From table 2 we can see that the dependence $T_1^{max}$ on $P_t$ is not too sharp and has a maximum on the segment $[3 \cdot 10^{-5}, 10^{-4}]$ that cannot greatly exceed 3.01 MPa. Therefore, it is clear that the strength condition $T_1^{max}$ is satisfied with a very good margin even if the ultimate stress is 110 MPa.
Figure 5 shows the result of modeling the mechanical stresses in MPa for the ME material metglas/(LiNbO₃ cut Y+140 °) at the flexural resonance mode for the lithium niobate layer.

![Figure 5](image_url)

**Figure 5.** Result of simulation of mechanical stresses (VonMises Stress) in MPa for ME material metglas/(LiNbO₃ cut Y+140 °) at flexural resonance mode for a 0.5 mm thick lithium niobate layer. The scale shows the value of mechanical stress in the material metglas/(LiNbO₃ cut Y+140 °) in MPa, arrows indicate the value and direction of the force.

Finally, let us make a similar calculation for a magnetoelectric composite, in which a thin narrow strip of gallium arsenide cut from the (001) layer in the <110> direction is used as a piezoelectric. Material constants for it $\rho = 5320 \, \text{kg/m}^3$, $s_{11}^E = 8.25 \times 10^{-12} \, \text{m}^2/\text{N}$, $\varepsilon_{33}^T = 12.9$, $d_{31} = -1.347 \times 10^{-11} \, \text{m/V}$.

Gallium arsenide yield strength 10 GPa.

The results of this calculation are presented in table 3.

| $\rho t, m$ | $f_r, \text{Hz}$ | $\rho T_{i}^{\text{max}}, \text{MPa}$ |
|----------|----------------|---------------------|
| $10^{-3}$ | 1285.0         | 1.02                |
| $5 \times 10^{-4}$ | 669.8         | 1.84                |
| $3 \times 10^{-4}$ | 425.3         | 2.69                |
| $10^{-4}$ | 185.2          | 4.48                |
| $5 \times 10^{-5}$ | 126.9         | 4.65                |
| $3 \times 10^{-5}$ | 103.5         | 4.18                |

From table 3 we can see that the dependence $\rho T_{i}^{\text{max}}$ on $\rho t$ is not too sharp and has a maximum on the segment $[3 \times 10^{-5}, 10^{-4}]$, which cannot greatly exceed 4.65 MPa. Therefore, it is clear that the strength condition $\rho T_{i}^{\text{max}}$ is satisfied with a very good margin. Figure 6 shows the result of modeling the mechanical stresses in MPa for the ME material metglas/GaAs at the flexural resonance mode for the GaAs layer.
Figure 6. Result of simulation of mechanical stresses (VonMises Stress) in MPa for ME material metglas/GaAs at flexural resonance mode for GaAs layer 0.5 mm thick. The scale shows the value of mechanical stress in the metglas/GaAs material in MPa, arrows indicate the value and direction of the force.

3. Conclusion
The article analyzes the strength of multiferroic layered structures in the designs of position sensors in order to understand the limits of the operation of these sensors. The strength test of magnetostrictive-piezoelectric two-layer structures metglas/PZT, metglas/(LiNbO3 cut Y+140°), metglas/GaAs was carried out in the bending mode of the magnetoelectric effect. It was found that in all cases the strength condition is satisfied with a very good margin. Thus, the reliability of position sensors with a magnetoelectric structure is fully ensured. The studies carried out open up obvious prospects for creating economical and cheap sensors for use in CPS structures, as well as electric motors for determining angular positions and other automated systems.

Acknowledgements
This research was funded by by RFBR project number № 19-58-18001. The article is related to the implementation of the project "Modeling and design of position sensors based on multiferroic layered structures" under Contract No. KII-06-Русна/20 28.09.2019, Todor Kableskov University of Transport – Sofia, on the Bulgarian side.

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