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Converse magnetoelectricity in asymmetric magnetoelectric structures

*G.S. Radchenko, M.G. Radchenko**

Institute of Physics, Southern Federal University,
194 Stachki Ave., 344090 Rostov-on-Don, Russia
Pedagogical Institute, Southern Federal University,
33 Bolshaya Sadovaya St., 344022 Rostov-on-Don, Russia
* Rostov Branch, Moscow State Technical University of Civil Aviation,
262b Sholokhova St., 344009 Rostov-on-Don, Russia

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A new computational approach is developed to analyze the asymmetric magnetoelectric structures. The possibility to enhance considerably the composite main effective parameters is found. The acoustic and electromagnetic vibrations in such structures are described comprehensively.

Развит новый вычислительный подход к анализу асимметричных магнитоэлектрических структур. Обнаружена возможность значительного усиления основных эффективных параметров композита. Приведено полное описание акустических и электромагнитных колебаний в таких структурах.

1. Introduction

The rapid development of modern electronics requires novel materials with useful properties. The promising magnetoelectric (ME) heterogeneous materials possessing converse ME effect (CMEF) are among materials of promise for practical applications. CMEF is the magnetization of a sample under external electric field. This offers an excellent potential for coil-free electromagnets free of eddy-current existence, devices for sensitivity measurements and for development of ME memory devices and sensors. In literature, the CMEF is a rather new direction and there are some publications aimed at that matter [1-10]. The structures considered in the present work and in [1, 3-5, 7, 8, 10, 11] are layered heterogeneous structures containing combination of highly magnetostrictive and piezoactive substances. The applied external electric field creates mechanical straining of the piezoelectric plate and then this strain is transferred to magnetic phase, causing a magnetic flux therein due to the magnetostriction. Then the created flux is registered by a testing coil [1, 3, 4, 7, 8, 10], two Helmholtz coils [5], one coil above the vibrating magnet [9], or vibrating sample magnetometer in heterostructures [2]. In the region where the applied electric field is of resonance frequency, the response is increased drastically and this provides a way for CMEF to be practically essential. However, almost all these publications are aimed at the symmetric strictures, there piezo- and magnetostrictive layers are of similar length. However, in reality, the lengths may be very different, and no attempts to analyze this difference theoretically were made prior to this work. The converse ME susceptibility is poorly analyzed in literature, too. This has stimulated the present research.

2. Theoretical analysis and results

Let us consider an asymmetric layered structure with different lengths of the components. The basic equations [11] for strain tensor component S_1 and electric and magnetic induction vectors component D_3 and B_1 as functions of the *x* coordinate (X_1 direction) can be written as follows (1).

$$S_1^p = s_{11}^p T_1^p(x) + d_{31}^p E_3^*$$

$$D_3^p(x) = d_{31}^p T_1^p(x) + \varepsilon_{33}^p E_3^* \qquad (1)$$

$$B_1^m(x) = q_{11}^m T_1^m(x) + \mu_{11}^m H_1^{bias}$$

$$S_1^m(x) = s_{11}^m T_1^m(x) + q_{11}^m H_1^{bias}.$$

Here s_{11}^p, d_{31}^p *and* ε_{33}^p are the elastic compliance, piezoelectric coefficient, and dielectric permittivity of piezoelectric, respectivegly; s_{11}^m, q_{11}^m *and* μ_{33}^m are the elastic compliance, magnetostrictive coefficient and magnetic permeability of ferrite, respectively. H_1^{bias} is the applied bias magnetic field; E_3^*, the electric field equal to the applied one. The mechanical coupling between the phases is supposed to be ideal.

Using the basic equation governing acoustic oscillations [12] and boundary conditions [11, 12], we get the expression for the strain vector (2)

$$u_x(x) = \frac{d_{31}^p h^p s_{11}^m L^p E_3^* + q_{11}^m h^m s_{11}^p L^m H_1^{bias}}{k\left(h^p L^p s_{11}^m \cos\left(\frac{kL^p}{2}\right) + h^m L^m s_{11}^p \cos\left(\frac{kL^m}{2}\right)\right)} \sin(kx). \qquad (2)$$

The expression (2) is derived for the first time and defines completely the strain of the plate-like sample due to converse ME interaction and different lengths of the plates. It takes into account the inertia forces and back moving forces of both the phases. Then we place the obtained result to the third equation of the set (1). The arising magnetic induction we obtain by averaging it.

The expression for the effective ME susceptibility, taking the above-mentioned average into account, is given by (3).

$$\alpha_{13}^* = 2\frac{d_{31}^p h^p s_{11}^m L^p q_{11}^m \sin\left(k\frac{L^m}{2}\right)}{kL^m\left(h^p L^p s_{11}^m \cos\left(\frac{kL^p}{2}\right) + h^m L^m s_{11}^p \cos\left(\frac{kL^m}{2}\right)\right)}. \qquad (3)$$

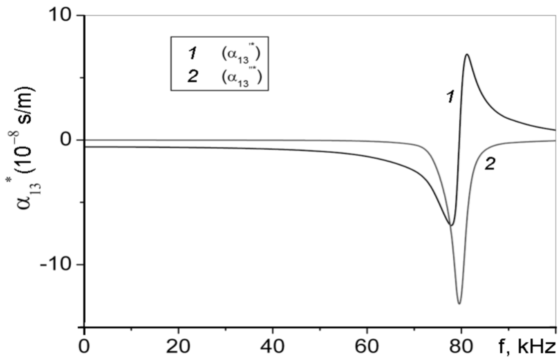

Fig. 1. Theoretical (3) frequency dependence of the *L-T* real and imaginary parts of ME susceptibility of PZT-Terfenol compound. The parameters for theory are: $s_{11}^p = 15{,}3 \cdot 10^{-12}$ m²/N, $d_{31}^p = -175$ pC/N; $s_{11}^m = 45{,}4 \cdot 10^{-12}$ m²/N; $q_{11}^m = 4500$ м/A; $\mu_{11}^m = 2{,}2 \cdot 10^{-6}$ Tm/A; $L^m = 14$ mm, $L^p = 16$ mm, $h^m = 1{,}2$ mm, $h^p = 2$ mm, $\chi = 8000$ rad/s, $\rho^m = 9200$ kg/m.

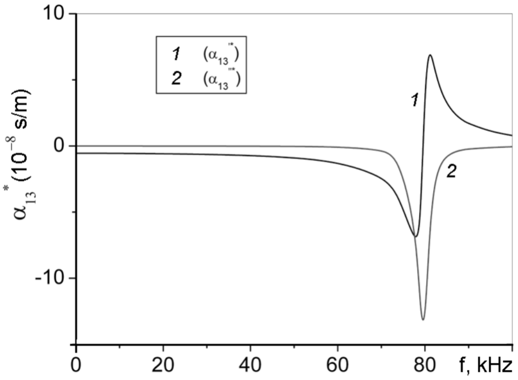

Fig. 2. Theoretical (4) frequency dependence of the real and imaginary parts of effective dielectric permittivity ε_{33}^* of PZT-Terfenol compound. The parameters for theory are the same as in Fig. 1.

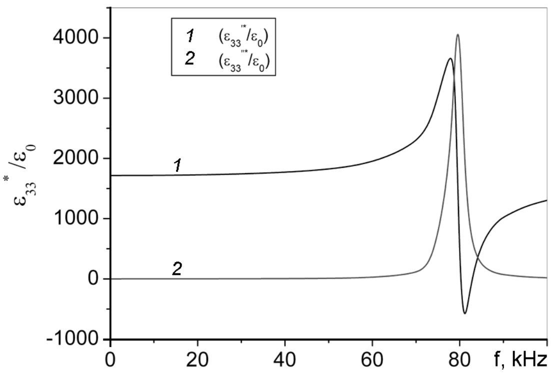

Figure 3. Theoretical (5) frequency dependence of the transversal real and imaginary parts of piezoelectric coefficient d_{31}^* of PZT-Terfenol compound. The parameters for theory are the same as in Fig. 1.

The lengths of the plates being taken to be the same, our formula turns into (6) from [4] and the model is analogous to [11]. To obtain the longitudinal coefficient α_{33}^*, we have to substitute q_{31}^m for q_{11}^m. It is usually much smaller than transversal due to the influence of demagnetization fields created by the metal electrode surface currents. The attenuation can be regarded as a complex angular frequency $\omega = 2\pi f + i\chi$.

We can also determine the effective dielectric response (4) which has another resonance frequency.

$$\varepsilon_{33}^* = \partial\left(\frac{1}{L}\int_{-L/2}^{L/2} D_3^p(x)dx\right)/\partial E_3^* = \varepsilon_{33}^p - \frac{\left(d_{31}^p\right)^2}{s_{11}^p} + 2\frac{\left(d_{31}^p\right)^2 h^p s_{11}^m \sin\left(k\frac{L^p}{2}\right)}{k s_{11}^p\left(h^p L^p s_{11}^m \cos\left(\frac{kL^p}{2}\right) + h^m L^m s_{11}^p \cos\left(\frac{kL^m}{2}\right)\right)}. \quad (4)$$

The dielectric response ε_{33}^* consists of frequency-independent part (rigidly fixed sample) and resonance dynamic part, which at $f \to 0$ transforms ε_{33}^* into the low-frequency response at constant stress.

It is impossible to divide the piezoelectric and magnetoelectric contributions to the strain (both phases vibrate in the same manner). Thus, to calculate the effective converse piezoresponse, we need to consider the strains in both the phases according to the average from the total strain. The effective piezoelectric coefficient is determined by formula (5)

$$d_{31}^* = 2\frac{d_{31}^p h^p s_{11}^m\left(L^p \sin\left(k\frac{L^m}{2}\right) + L^m \sin\left(k\frac{L^p}{2}\right)\right)}{kL^m\left(h^p L^p s_{11}^m \cos\left(\frac{kL^p}{2}\right) + h^m L^m s_{11}^p \cos\left(\frac{kL^m}{2}\right)\right)}. \quad (5)$$

The resonance frequencies are determined by assuming the denominators in (3-5) to zero and are dependent on the elastic properties of both the phases and their volume densities and all the dimensions. If the oscillations of the external electric field are at the resonance frequencies, the sharp increase of induced magnetic induction (3), dynamic polarization (4), and mechanical vibrations (5) will occur in the sample.

The physical nature of resonance frequency independence of other integral composite parameters in this work and in [4], in contrast to [11], consists in what follows. The magnetic field and magnetic induction play opposite parts in the electromagnetic interactions in comparison with electric field and induction. This results, for example, in the absence of the average induced magnetic field H inside the sample due to the converse effect. The ME voltage coefficient is determined in [11] under open electric chain conditions (average D is equal to zero) as E/H comprises fields which play physically opposite roles. Therefore, a_E depends upon most of the integral parameters.

The attenuation can be regarded as a complex angular frequency $\omega = \omega' + i\chi$. Here χ is the attenuation parameter. So we also take into account the attenuation as it was done in [11] for direct effect and in [4] for converse one. The resonant enhancements of the most important physical constants are shown in Figs. 1-3. All the considered effective constants show a large resonance enhancement (both in real and imaginary parts). At low frequencies, the ME and other constants are much lower and practically independent of the frequency.

3. Conclusion

So, in this work we have investigated and analyzed the converse magnetoelectric effect within the frames of resonance theory. The considerable resonance enhancement of basic effective parameter in plate-like ME composites is shown. These results can help in designing of ME devices, magnetostrictive and piezoelectric transducers, actuators, and other technical devices.

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Зворотна магнітоелектричність в асиметричних магнітоелектричних структурах

Г.С.Радченко, М.Г.Радченко

Розвинуто новий обчислювальний підхід до аналізу асиметричних магнітоелектричних структур. Виявлено можливість значного підсилення основних ефективних параметрів композиту. Подано повний опис акустичних та електромагнітних коливань у таких структурах.