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Effect of magnetic field on magnetoelastic dynamics of films with manganese-zinc spinel parameters in the region of magnetic phase transition

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Received April 30, 2025
Revised September 8, 2025
Accepted November 11, 2025

Based on numerical solutions of the equations of magnetic dynamics and elasticity, the temperature dependences of the components of the magnetization vector and elastic displacement, the coefficients of magnetic and elastic attenuation, and the frequencies of magnetic and elastic oscillations for a film with the parameters of manganese-zinc spinel (MZS) were obtained at different values of the constant magnetic field directed perpendicular to the plane of the film. In the temperature range of 250−270 K, in which the sign inversion of the first constant of magnetic anisotropy for the MZS crystal is observed, deep and wide maxima are observed for the coefficients of magnetic and elastic attenuation, and deep and wide minima are observed for the frequencies of magnetic oscillations.

Keywords: Magnetic phase transition, temperature magnetoelastic dynamics, nonlinear effects.

DOI: 10.61011/PSS.2025.12.63105.8084k-25

In recent years, there has been a growing interest in the study of nonlinear magnetically elastic dynamics of magnetic materials, especially for the creation of new, ultra-fast, compact, and energy-efficient electronic and spintronic applications [1–4]. At the same time, there are few studies on nonlinear magnetoacoustic properties of crystals in the field of magnetic phase transitions, and most of them are the work of the authors of this article [5–9]. This is attributable to the presence of large nonlinearity of magnetic and elastic vibrations and giant attenuation in the field of magnetic phase transitions. The new effects discovered in this area can be used in various nonlinear devices, from high-frequency converters to ultra-sensitive magnetic field sensors and microwave electromagnetic radiation absorbers over a wide temperature range.

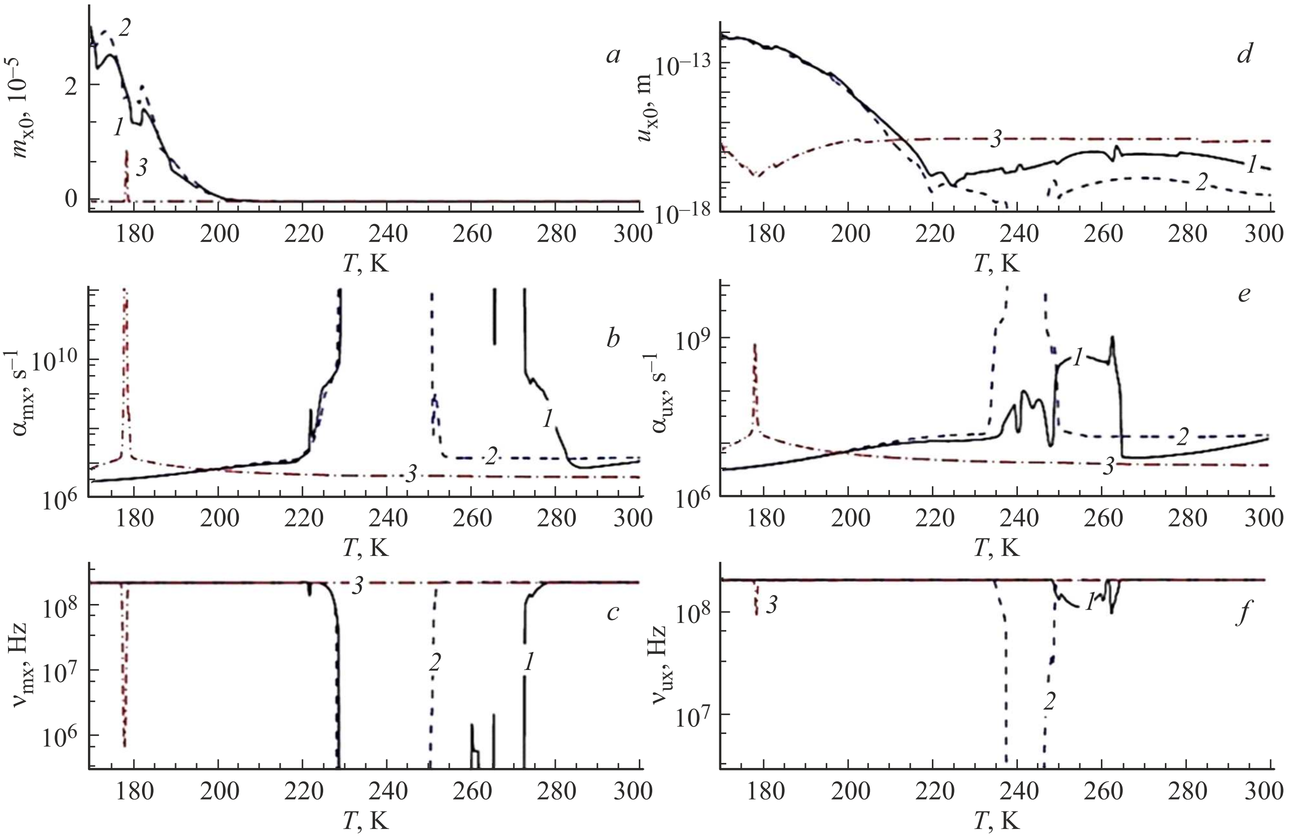
The calculation of temperature dependences of amplitudes and attenuation coefficients of magnetic and elastic vibrations of a magnetic crystal was carried out on the basis of solving a complete system of differential equations describing magnetic and elastic dynamics [5,10–12]. A solution to the system of equations was found for the parameters of a manganese-zinc spinel (MZS) crystal of nonstoichiometric composition $Mn_{0.61}Zn_{0.35}Fe_{2.04}O_4$, for which a change in the sign of the first magnetic anisotropy constant is observed K_1 in a zero constant magnetic field with a temperature change [5,13]. It was assumed that the total energy of the crystalline film is equal to the sum of the magnetic, elastic, and magnetically elastic energies. The systems of equations of magnetic and elastic dynamics were solved by the Runge−Kutta−Felberg method of the 7−8th order with control of the integration step length [5,11]

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma[\mathbf{m} \times \mathbf{H}_e] + \alpha\left[\mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}\right], \tag{1}$$

$$\frac{\partial^2 u_{x,y}}{\partial t^2} = -2\beta\,\frac{\partial u_{x,y}}{\partial t} + \frac{c_{44}}{\rho}\,\frac{\partial^2 u_{x,y}}{\partial z^2}, \tag{2}$$

$$\begin{aligned} U = {} & -M_0 h_x m_x - M_0 h_y m_y - M_0 H_0 m_z + 2\pi M_0^2 m_z^2 \\ & + K_1(m_x^2 m_y^2 + m_x^2 m_z^2 + m_z^2 m_y^2) \\ & + K_2 m_x^2 m_y^2 m_z^2 + 2c_{44}(u_{xy}^2 + u_{yz}^2 + u_{zx}^2) \\ & + 2B_2(m_x m_y u_{xy} + m_y m_z u_{yz} + m_z m_x u_{zx}), \end{aligned} \tag{3}$$

where $\mathbf{m} = \mathbf{M}/M_0$ is the unit magnetization vector, M_0 is the saturation magnetization, H_0 is the permanent magnetic field strength, K_1, K_2 is the crystallographic magnetic field constants crystal anisotropy, $u_{i,j}$ is the elastic displacement components, c_{44} is the second-order elasticity constant, B_2 is the magnetoelastic coupling constant for transverse elastic vibrations, γ is the gyromagnetic ratio for electron spin, $\mathbf{H}_e$ is the intensity vector of the effective magnetic field acting on the magnetic moment, α is the magnetic dissipation parameter, β is the attenuation rate elastic vibrations, ρ is the crystal density. The diagonal components u_{ij} were not taken into account in the equation (3), since only transverse elastic vibrations were considered in this work. The expression for the volumetric energy density



Temperature dependences of the parameters of magnetic (a, b, c) and elastic (d, e, f) vibrations: amplitudes of the magnetization component m_{x0} (a) and elastic displacement u_{x0} (d); magnetic vibration attenuation coefficients α_{mx} (b) and elastic displacement vibrations α_{ux} (e), the frequencies of magnetic vibrations ν_{mx} (c) and elastic vibrations ν_{ux} (f). A permanent magnetic field is applied perpendicular to the film plane with inductions B_0: 0.2, 2 and 20 mT — curves *1,2* and *3*, respectively. The alternating magnetic field is directed along the axis Oy.

took into account the internal parameters of the crystal film and the parameters of the alternating and permanent magnetic fields. Expressions for effective magnetic, elastic, and magnetically elastic fields were obtained using the variation derivative, which were used in solving the equation of motion of magnetization (1). The obtained solutions for the magnetization components were substituted into the equation of elastic vibrations, where the connection of parts of the equations of elastic and magnetic nature was carried out through the introduction of a dependence into the elastic component, which took into account the contribution of the reduced magnetization components, as well as through boundary conditions, which took into account a similar dependence. Most of the parameters of the MZS crystal were chosen the same as in Ref. [6]: $\rho = 5.4 \cdot 10^3$ kg/m^3 over the entire temperature range; elastic attenuation parameter $\beta = 1.5 \cdot 10^6$ s^{-1}; elasticity constant $c_{44} = 7.64 \cdot 10^{10}$ J $\cdot$ m^{-3}; magnetoelastic interaction constant $B_2 = -3.96 \cdot 10^6$ J $\cdot$ m^{-3}, saturation magnetization value at room temperature $M_S = 38.25 \cdot 10^{-3}$ T; the film thickness was $d = 10\,\mu$m; the amplitude of the alternating magnetic field was 1 mT, the frequency of the alternating field was 180 MHz, which corresponded to the frequency of acoustic resonance at such a thickness. The frequency of the alternating magnetic field was chosen to be equal to the frequency of the acoustic resonance of the MZS film, with a thickness of $10\,\mu$m [14]. The alternating magnetic field was directed along the axis Oy, and the constant magnetic field was directed along the axis Oz and perpendicular to the plane of the film MZS.

The figure shows the temperature dependences of the maximum components of magnetization m_x (a) and elastic displacement u_x (d), attenuation coefficients (b, e) and the frequencies of magnetic (c) and elastic (f) vibrations under three external magnetic fields with inductions of 0.2, 2, 20 mT directed perpendicular to the plane of the MZS film.

The magnetization component m_x with all magnetic fields from 0.2 to 20 mT is close to zero in the temperature range from 200 to 300 K. As the temperature decreases from 200 to 170 K, the amplitude of the magnetization component m_x sharply increases to $2.5 \cdot 10^{-5}$. At low temperatures, the magnetization vector is directed along the crystallographic axis [111], while with decreasing temperature, the modules of the anisotropy constants K_1, K_2 increase strongly [6]. Two local maxima are observed at 175 and 185 K with magnetic fields of 0.2, 2 mT, which may be associated with a significant deviation of the magnetization vector **M** from the crystallographic axes [111] and [$1\bar{1}1$] and an approach to axes Oz. The external magnetic field is close in magnitude to the magnetic anisotropy field at these temperatures. The component m_x remains almost constant with a large magnetic field of 20 mT over the entire temperature range of 165–300 K with the exception of the temperature neighborhood of 178 K, in which a narrow peak is observed due to the ferromagnetic resonance [6].

Let us describe the behavior of the temperature dependences of the amplitude of the elastic displacement component u_x in the temperature range from 170 to 300 K at three magnetic fields with inductions of 0.2, 2, 20 mT (Figure, *d*). As can be seen from the figure, *d*, the amplitude of u_x first decreases at a low magnetic field of 0.2 mT with an increase in temperature from 175 to 273 K and then slightly increases in the range of 220–273 K, and then drops again near 300 K. This temperature dependence $u_x(T)$ correlates well with the behavior of the temperature dependence of the anisotropy field [6]. Consequently, the amplitude of u_x is largely determined by the magnitude of the anisotropy field of the MZS crystal in the studied temperature range at low magnetic fields. The temperature dependence of the amplitude of the elastic displacement $u_x(T)$ for the MZS film when placed in a magnetic field of 2 mT is similar to the dependence $u_x(T)$ at a magnetic field of 0.2 mT. The only difference between dependencies is that the minimum for dependencies $u_x(T)$ shifts from 220 to 240 K. The amplitude u_x is close to zero in the temperature range of 240–250 K at a magnetic field of 2 mT, and an order of magnitude smaller than in the case of a magnetic field of 0.2 mT. Based on the dependence of the amplitude of the elastic displacement $u_x(T)$ for the MZS film in a magnetic field with an induction of 20 mT, a local minimum is observed at 180 K, which is most likely due to FMR and is associated with resonant energy transfer from elastic vibrations to magnetic vibrations in the magnetic resonance region.

As can be seen from the figure, *b* a maximum is observed in the temperature range of 230–273 K on the temperature dependences of the attenuation coefficient of the magnetic component $m_x(T)$ in a small magnetic field 0.2 mT, where the magnetic anisotropy fields in the MZS crystal tend to zero. The right side of the maximum curve shifts towards low temperatures from 273 to 250 K in a magnetic field of 2 mT. In a magnetic field with a high induction of 20 mT, the attenuation coefficient α_{mx} remains constant over the entire temperature range from 190 to 300 K. A narrow resonant peak is observed on the temperature dependence $\alpha_{mx}(T)$ at a temperature of 180 K, which is most likely associated with FMR.

As can be seen from the figure, *e*, a maximum is observed in a small magnetic field of 0.2 mT, on the temperature dependence of the attenuation coefficient of the amplitude of elastic displacements $\alpha_{ux}(T)$ in the temperature range of 235–265 K with several local maxima and minima corresponding to reorientation and different directions of the magnetization vector. The right side of the maximum curve shifts towards low temperatures from 265 to 250 K in a magnetic field of 2 mT. The coefficient α_{mx} in the temperature range from 185 to 300 K is practically independent of temperature in a magnetic field with a high induction of 20 mT. A narrow resonant peak is observed on the dependence $\alpha_{mx}(T)$ at a temperature of 180 K, which is associated with FMR, observed at the same temperature.

As can be seen from the figure, *c*, a deep minimum is observed in a small magnetic field on the temperature dependence of the frequency of magnetic oscillations $\nu_{mx}(T)$ in the temperature range of 230–273 K, in which the frequency of magnetic oscillations decreases by more than two orders of magnitude. Two local narrow maxima are observed at 260 and 265 K in the minimum region, which are most likely related to the processes of reorientation of the magnetization vector at these temperatures. The right side of the minimum curve shifts towards low temperatures from 273 to 250 K in a magnetic field of 2 mT. In a large magnetic field with an induction of 20 mT, the frequency of magnetic oscillations is practically independent of temperature and is equal to the frequency of an external alternating magnetic field of 180 MHz. At a temperature of 178 K, at which the FMR condition is fulfilled, a narrow minimum is observed, in which the frequency of magnetic oscillations decreases from 150 MHz to 0.9 MHz.

As can be seen from the figure, *f*, a shallow wide minimum is observed in a small magnetic field of 0.2 mT on the temperature dependences of the frequency of elastic vibrations $\nu_{ux}(T)$ in the temperature range of 250–265 K: the frequency of elastic vibrations decreases from 180 MHz up to 100 MHz. A local maximum and minimum are observed at temperatures of 262 and 265 K in the region of this wide minimum, which may also be associated with the processes of reorientation of the magnetization vector. The minimum $\nu_{ux}(T)$ shifts towards low temperatures in a magnetic field with induction 2 mT and is observed at temperatures of 235–250 K. The frequency of elastic vibrations in the minimum region decreases by more than an order of magnitude, from 180 to 8 MHz. In a large magnetic field of 20 mT, the frequency of elastic vibrations is practically independent of temperature and is equal to the frequency of an external alternating magnetic field 180 MHz, with the exception of the temperature neighborhood of 180 K, at which the condition FMR is fulfilled.

In this work, based on numerical solutions of the equations of magnetic dynamics and elasticity, the temperature dependences of the components of the magnetization vector and elastic displacement, the coefficients of magnetic and elastic attenuation, as well as the frequencies of magnetic and elastic vibrations for the MZS film of nonstoichiometric composition $Mn_{0.61}Zn_{0.35}Fe_{2.04}O_4$, thickness 10 μm, for different values of a constant magnetic field with inductions B equal to 0.2, 2 and 20 mT directed perpendicular to the film plane. It was found that in the temperature range of 250–270 K, deep minima are observed for the magnetic oscillation frequencies of the MZS film, in which the frequencies decrease by more than an order of magnitude. A comparison of the obtained theoretical temperature dependences of the attenuation coefficients of elastic vibrations of the MZS film with similar experimental temperature dependences obtained in Ref. [15] shows that the qualitative type of change in the attenuation coefficients of elastic vibrations with temperature changes is close to the observed changes in a real MZS crystal of a similar nonstoichiometric composition. The results show that using a constant magnetic field with a small induction, it is possible to control the parameters of the temperature maxima of the attenuation coefficients of magnetic and elastic vibrations.

Funding

The study was carried out at the expense of a grant from the Russian Science Foundation (RSF), project no. 25-72-20063.

Conflict of interest

The authors declare no conflict of interest.

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Translated by A.Akhtyamov