Hypersound excitation of three-layer magnetic film by microwave field

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Abstract.
The work deals with the definition of elastic and magnetic oscillations exited by microwave magnetic field in the three-layer structure. The frequency dependences for the amplitudes of the magnetic and elastic vibrations of the film layers with different values of the material parameters and amplitudes of the external fields are calculated.

1. Introduction
In the last decade, the control of magnetization dynamics under the influence of elastic waves at frequencies up to 500 GHz is a rapidly developing area of magnetoacoustics [1, 2]. This paper continue above mentioned works and is devoted to solving the problem of magnetic and elastic dynamics in a three-layer film in the most general nonlinear case. Based on the results of studies of the dynamics of a three-layer magnetic structure, a generator of hypersonic vibrations can be constructed. This generator can be used in various electronic devices, for example, in medicine for diagnose of the internal organs.

2. Geometry of the problem and main equations
Fig. 1 shows the geometry of the problem. The paper deals with a three-layer film consisting of three magnetic layers. The thickness of the layers was in the range from 0.2 to 0.6 μm. Mark the film layers with the letters p, d, r. The thickness of the layers by the same letters will be denoted. The center of the coordinate system is selected in the center of the d layer. The DC magnetic field $H$ was directed perpendicular to the film plane along the z-axis. The alternating magnetic field $h$ was directed in plane of the structure and has a circular polarization.

The total thickness of the film is equal to half of the elastic wavelength. Elastic frequency is close to ferromagnetic resonance frequency (FMR). We assume that all layers have the same elastic properties.

The film’s layers have a cubic crystallographic symmetry; the crystallographic plane (100) coincides with the plane of the plate. The total energy density of the film’s layers $U$ in the field $H_{ext} = \{h_x; h_y; H\}$ as the sum of the energy density of each layer is considered. The energy density of each layer includes the density of magnetic, magnetoelastic, elastic energy and anisotropy energy. We consider the interaction of the standing on the film thickness shear elastic waves with magnetic oscillations only. The energy density will have form [3]:

$$
U = -M_0 h_x m_x - M_0 h_y m_y - M_0 H m_z + 2\pi M_0^2 m_z^2 + 2B_2 (m_x m_y u_{xy} + m_y m_z u_{yz} + m_z m_x u_{zx}) + 2C_{44} (u_{xy}^2 + u_{yx}^2 + u_{xx}^2) + K_1 (m_y^2 m_x^2 + m_x^2 m_z^2 + m_z^2 m_y^2) + K_2 m_x^2 m_y^2 m_z^2
$$

(1)
where $M_0$ - saturation magnetization, $m_i$ - components of unit magnetization vector, $B_2$ – magnetoelastic constant, $C_{44}$ - elastic constant, $u_{ik}$ – displacements tensor components, $K_1, K_2$ – first and second cubic anisotropy constants.

![Figure 1. Geometry of the problem.](image)

We divide the solution for elastic displacement into 2 parts:

\[ u_X(z, t) = U_X(z, t) + v_X(z, t), \]

where $U_x$ - the inhomogeneous part of the solution, for this part following condition is valid: $\partial^2 U/\partial z^2 = 0$ in all thickness and boundaries, $v_x(z, t)$ – the part satisfies the homogeneous boundary condition ($\partial v/\partial z = 0$ on the external boundaries). The equality of the $v$ functions and its derivations $\partial v/\partial z$ is on the internal boundaries between layers. We decompose the homogeneous part by eigenfunctions of the boundary value problem over the internal layer thickness (for example, p layer) in order to take off the coordinate dependence. As the result, we obtain:

\[ v_{px}(z, t) = v_{0px}(t) + \sum_{n=1}^{\infty} v_{pn}(t) \cdot \cos \left( \frac{\pi \cdot n}{p} \cdot z + \frac{\pi \cdot n}{p} \cdot \frac{d}{2} \right) \]  

We substitute $v_{0px}(t)$, $v_{0py}(t)$ values expressed by equation (3) to magnetoelastic equations and use equation for $U$. We can obtain following differential equations:

\[ \frac{d^2 v_{1x}}{dt^2} + 2\beta \frac{d v_{1x}}{dt} + \frac{c_{44}}{\rho} \cdot \frac{\pi^2}{p^2} v_{1x} = -\frac{4p}{\pi^2} \left( \frac{d^2}{dt^2} + 2\beta \frac{d}{dt} \right) \left( -\frac{B_{p2}}{c_{44}} m_{px} m_{pz} \right) \]

\[ \left( \frac{d^2}{dt^2} + 2\beta \frac{d}{dt} \right) \left( v_{0px}(t) + \frac{B_{p2}}{c_{44}} m_{px} m_{pz} + \frac{B_{d2}}{c_{44}} m_{dx} m_{dz} \right) = 0. \]

We can find similar equations for the $y$-components by the changing $x$ to $y$ index. The similar mathematical manipulations we repeat for the other two layers. Thus, we obtain the system of ordinary differential equations, including the Landau-Lifshitz-Gilbert equation, equations of type (4), (5) for $x$. 

![Side view](image)
and y elastic displacements components for all three layers. Coupling between the layers in our model was carried out by the zero terms Fourier decomposition.

3. Results and discussions

The Runge-Kutta 4-5 orders method to solve the system differential equations was used. The frequency of the alternating field corresponded to the resonant frequency of the elastic oscillations of the film. The main parameters of the film material corresponded to the parameters of yttrium-iron garnet crystals. The time dependences of the magnetization and the elastic displacements for various frequencies were plotted. The resonance curves for the cases of linear and nonlinear oscillations were plotted (Fig. 2).

![Figure 2](image)

**Figure 2.** Frequency curves in the linear ($h=10\text{Oe}$) (a) and nonlinear ($h=200\text{Oe}$) (b) cases. $H_0=2750\text{Oe}$; $4\pi M_0$ (in Gs) =1700 (i=p), 1750 (i=d), 1800 (i=r); $B_2=13.92\times10^6$ erg cm$^3$.

The maxima of the amplitudes of the magnetic and elastic oscillations are observed at the alternating field frequency close to the FMR frequency. The slope of the resonance curves is observed at large amplitudes of the alternating field. This slope is for the nonlinear case. The interesting dynamics is observed for the condition when the external constant field is close to the demagnetization field $H=4\pi M_0$. In this case, the second-order magnetization precession modes were revealed. These regimes were previously observed for one ferrite layer in [4-5]. Due to the difference of the gyroscopic forces that are exerted on the magnetization vector at the positions of the maximum and minimum displacements relative to the axis $z$, the equilibrium position of the magnetization vector is shifted and average in time magnetization vector is involve in the precession along a large circle, so that the precession of equilibrium position takes place. Fig. 3 shows precession portraits of magnetization in the film layers with very different values of the magnetoelastic constants of the layers. The tendency of p layer magnetization to follow position of a new easy axis, different from the normal to the film plane is observed for Fig. 3 (a). This phenomenon occurs in a material with large magnetoelastic constants [3]. The precession regimes of the equilibrium position of the magnetization vector without the center coverage (in layer d and r) and with the center coverage (in layer p) are found. It is possible to distinguish the maximum amplitudes of the oscillations in layers at low frequencies (about 0.5 GHz) and at the high frequencies (about 25 GHz) taking into account these two oscillation modes.
Figure 3. Precession portraits of the magnetization in different layers of the three-layer structure. The amplitude of the alternating magnetic field $h=1$ Oe (a), 20 Oe (b). $4\pi M_0 - H = 5$ Oe. $H=1750$ Oe; $4\pi M_0=1755$ Gs; value of the magnetic dissipation parameter $\alpha=0.1$, $B_{p2}=13.92 \times 10^5$ erg cm$^{-3}$, $B_{d2}=13.92 \times 10^6$ erg cm$^{-3}$, $B_{r2}=13.92 \times 10^7$ erg cm$^{-3}$.

4. Conclusions
This paper solves the problem of magnetic and elastic dynamics in a three-layer film in the most general nonlinear case. The generator of hypersonic vibrations can be constructed based on the results of studies of the dynamics of the structure. We can vary amplification coefficient of the elastic oscillations in the wide frequency range due to the presence of the magnetic and magnetoelastic coupling between the layers. The materials of the three-layer films can be metal-dielectric composite [6-7] or complex materials with extreme dynamic strength [8].

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