УДК 537.9

# Nonlinear Magnetoelastic Dynamics of the Ferrite Plate

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Received 16.08.2016, received in revised form 21.10.2016, accepted 15.11.2016

*The present work deals with investigation of features of a magnetization vector of nonlinear precession and elastic displacements close to ferromagnetic resonance in normal magnetized ferrite plate. The processes of frequency division and frequency multiplication were considered in the research.*

*Keywords: Nonlinear magnetoacoustic, ferrite plate, ferromagnetic resonance.*
DOI: 10.17516/1997-1397-2017-10-1-36-39.

Problem of excitation of ultrasound oscillations by use of alternating magnetic field in normal magnetized plate is considered in the paper. Processes of parametric excitation and related losses can be prevented by choosing this geometry[1, 2].

The present work deals with investigation of the features of processes of alternating field frequency division and frequency multiplication close to ferromagnetic resonance.

## 1. Geometry of the problem and basic equations

The plane-parallel plate has thickness $d$. The external dc magnetic field $H_0$ is applied perpendicular to plane of the plate. The problem is solved in a Cartesian coordinate system $Oxyz$. The plane $Oxy$ of the coordinate system coincides with the plane of the plate. The coordinate axes are parallel to the edges of the cube crystallographic cell. The center of the coordinate system $O$ is in the center of the plate, so that the plate planes coordinates are $z = \pm d/2$. We consider only excitement of the transverse elastic oscillations.

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Assuming that the total energy density of the plate $U$ in the field $\vec{H} = \{h_x; h_y; H_0\}$ equals the sum of magnetic, elastic and magnetoelastic energy densities, we obtain:

$$U = -M_0 h_x m_x - M_0 h_y m_y - M_0 H_0 m_z + 2\pi M_0^2 m_z^2 + 2c_{44}(u_{xy}^2 + u_{yz}^2 + u_{zx}^2) + \\ + 2B_2(m_x m_y u_{xy} + m_y m_z u_{yz} + m_z m_x u_{zx}), \quad (1)$$

where $\vec{m} = \vec{M}/M_0$ is normalized magnetization vector, $M_0$ is the saturation magnetization.

The initial equations for the system are the Landau-Lifshitz-Gilbert equation and the equations for the elastic displacement vector components $u_{x,y}$:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \left[\vec{m} \times \vec{H}_e\right] + \alpha \left[\vec{m} \times \frac{\partial \vec{m}}{\partial t}\right], \quad (2)$$

$$\frac{\partial^2 u_{x,y}}{\partial t^2} = -2\beta \frac{\partial u_{x,y}}{\partial t} + \frac{c_{44}}{\rho} \cdot \frac{\partial^2 u_{x,y}}{\partial z^2}. \quad (3)$$

Boundary conditions are:

$$c_{44} \frac{\partial u_{x,y}}{\partial z} \Big|_{z=\pm d/2} = -B_2 m_{x,y} m_z. \quad (4)$$

The system of the equations was solved numerically by the Runge-Kutta 7–8 orders method with control of the integration at every step length.

The material parameters used in the calculation are typical for crystals YIG: $4\pi M_0 = 1750\ Gs$, $c_{44} = 7.64 \cdot 10^{11}\ erg \cdot cm^{-3}$, $\rho = 5.17\ g \cdot cm^{-3}$.

Elastic oscillations were detected on the surface of the magnetic plate where $z = d/2$.

## 2. Frequency division

The system was configured in such a way that the frequency of elastic resonance was multiple of ferromagnetic resonance frequencies. Thickness of the plane was selected multiple of resonance thickness i.e. $d = n \cdot d_r$, where $n$ is multiplicity.

The process of frequency division is followed by two transient regimes connected with relaxations of elastic and magnetic oscillations. Optimum conditions for frequency division can be traced over the range from $1.5 \cdot 10^{-8}$ sec to $2.0 \cdot 10^{-8}$ sec, when relaxation of magnetic oscillations finishes whereas relaxation of elastic oscillations does not appear.

Frequency of magnetic oscillation remains equal to excitation frequency and the phase portrait keeps a circular symmetry (Fig. 1a, b, c, d). However, frequency of elastic oscillations becomes two times lower than frequency of magnetic oscillations and the amplitude interleave stops. The phase portrait takes the shape of a well-defined circle, which looks like triangle with intense rounded corners and shape similar to a circle.

In order to divide to frequency we make a system in such a way that thickness of the plate is thicker in multiple relation than thickness, which corresponds to magnetic resonance, i.e. $d = n \cdot d_r$, where $n$ is multiplicity, $d_r$ is resonance thickness, $d$ is thickness of the plate.

It can be seen from Fig. 1e, f, g, h that the period of elastic oscillations exceeds the excitation period in the same number of times as thickness of a plate exceeds resonance thickness. The shape of oscillations corresponds to the sinusoidal form in case of halving or trisection. The shape distortion takes place in case of multiplicity increase due to undesired oscillation that occur on excitations frequency.

Amplitude of basic excited oscillations increases with increase of division multiplicity. If $n$=2, the amplitude is $2.7 \cdot 10^{-9}$ cm, if $n$=4, the amplitude is $7.5 \cdot 10^{-9}$ cm, if $n$=6, the amplitude is $15.0 \cdot 10^{-9}$ cm. This increase of the amplitude is determined by energy storage of exciting magnetic oscillations during the period of elastic oscillations.

The phase portrait of elastic oscillations has a shape of curvilinear polygon with sharp corners. The more is multiplicity, the sharper are the corners. Number of corners exceeds once the multiplicity division due to the phase quadrature between $u_x$ and $u_y$ components of excited elastic oscillations combined with a small contribution component of exciting frequency in base oscillations.

It should be noted that, the amplitude of y-component is always less than the amplitude of $x$-component, at that this difference grows with the growth of multiplicity division.

## 3. Frequency multiplication

The system was made in such a way that the frequency of elastic resonance was bigger in multiply relation than frequency of the magnetic resonance.

Frequency multiplication optimum conditions are similar to frequency division. However, our studies revealed that frequency multiplication requires linear polarization of excitation signal in case of nonlinear regime: $h_x = 1000$ Oe, $h_y = 0$ Oe.

The time-base sweep of elastic displacement and corresponding phase portrait at various thicknesses of magnetic plate are shown in Fig. 1i, j, k, l.

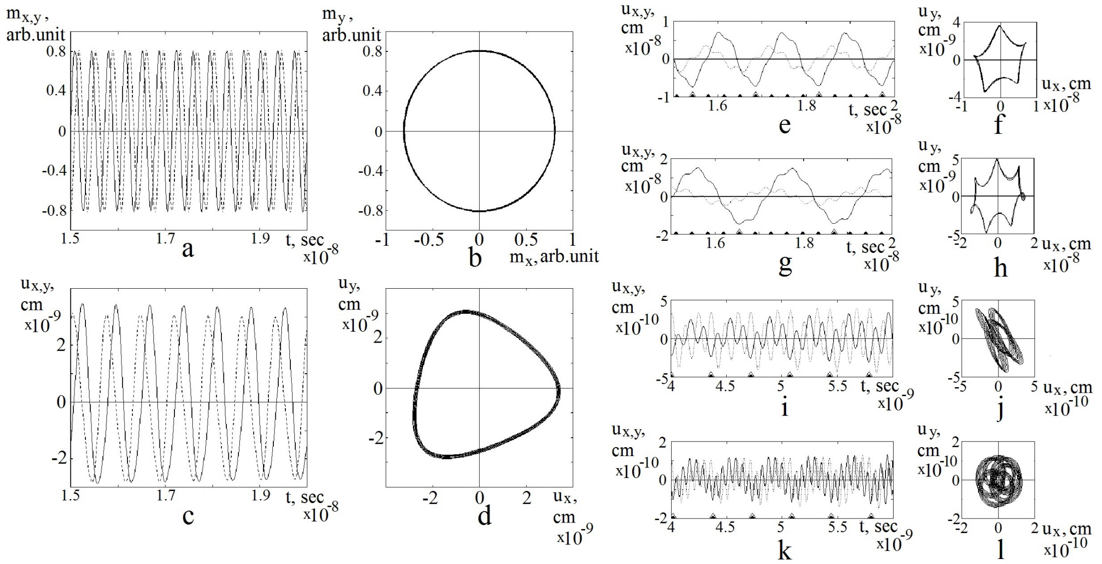


Fig. 1. Development of magnetic oscillations as well as elastic oscillations and the corresponding phase portraits in nonlinear regime ($h_{x,y} = 1000$ $Oe$). The case of frequency division (a, b, c, d, e, f, g, h) and multiplication (i,j,k,l). Thickness of the plate: a,b,c,d — $d = 2 \cdot d_r$; e, f — $d = 4 \cdot d_r$; g, h — $d = 6 \cdot d_r$; i, j — $d = d_r/3$; k, l — $d = d_r/6$. Black triangles are periods of the excitation signal. Unshaded triangles are periods of the excited elastic oscillations. Frequency of the alternating field — $2.8 \cdot 10^9$ $Hz$, $H_0 = 2750$ $Oe$, $d_r = 68.65 \cdot 10^{-9}$ $cm$

We can see that amplitudes of both elastic components differ from each other by 10% in spite oflinear polarization of the exciting field. This is due to the fact that the precession of magnetization has gyrotropic properties and it leads to the fact that it gets almost a circular shape in case of linear polarization.

The component on fundamental mode oscillation frequency occurs in all cases apart from multiplication frequency component. We've noticed that this occurrence is increasing in case of multiplicity increase.

Phase portraits in all cases have a circular shape, they are sharply defined and get the shape of two osculant interleaved rings only if multiplicity equals two. Circular phase trajectories progressively move away from each other in case of the multiplicity increaseand as aresult they get the shape of mutual braided rings. The shape of these ring become more complicated the bigger is the order of multiplicity.

## Conclusion

Thus, the coupled oscillations of magnetization and elastic displacement in normally magnetized ferrite plate that possess magnetoelastic properties are considered in the paper. These oscillations are excited by the alternating magnetic field, where frequency is the same as FMR frequency of the magnetic subsystem.

Processes of frequency division and multiplication are possible only when regime of excitement is nonlinear. In case of multiplication, polarization of excitation alternating field should be linear.

The shape of oscillations is close to sinusoidal in case of low integer multiplicity and is different from this form in case of high integer multiplicity under multiplication of frequency. Component of exciting frequency is dominant over component of multiple frequency.

Correlation of division and multiplication processes with times of magnetic and elastic relaxations are described. Stable processes exist when relaxation time of elastic oscillations are bigger by an order of magnitude than relaxation time of magnetic oscillations.

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## Нелинейная магнитоупругая динамика ферритовой пластины

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*В работе рассмотрены вынужденные колебания вектора намагниченности и упругого смещения вблизи ферромагнитного резонанса в нормально намагниченной ферритовой пластине. Представлены случаи деления и умножения исходной частоты.*

*Ключевые слова: нелинейная магнитоакустика, ферромагнитный резонанс.*