MAGNETIC SUSCEPTIBILITY TENSOR OF THE COMPOSITE MATERIAL CONSISTING OF SINGLE-DOMAIN MAGNETIC PARTICLES WITH UNIAXIAL MAGNETIC ANISOTROPY

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Abstract — Using the Smit — Suhl method, we have calculated the magnetic susceptibility tensor of magnetized ferromagnetic media with the uniaxial magnetocrystalline anisotropy. An analysis of the obtained formulas in the particular cases of a composite material with randomly oriented ferromagnetic inclusions of ellipsoidal shape has been carried out.

ТЕНЗОР МАГНИТНОЙ ВОСПРИИМЧИВОСТИ КОМПОЗИЦИОННОГО МАТЕРИАЛА СОСТОЯЩЕГО ИЗ ОДНОДОМЕННЫХ МАГНИТНЫХ ЧАСТИЦ С ОДНООСНОЙ МАГНИТНОЙ АНИЗОТРОПИЕЙ

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Аннотация — В работе методом Смита — Сула проведен расчет тензора магнитной восприимчивости намагниченного ферромагнитного материала с одноосной магнитокристаллической анизотропией. Проведен анализ полученных соотношений для композитного материала, содержащего хаотически ориентированные магнитные частицы эллипсоидальной формы.

I. Introduction

In the analysis of the interaction of electromagnetic waves with a magnetized anisotropic ferromagnetic medium, it is necessary to have knowledge of the components of the permeability tensor $\vec{\mu} = \vec{1} + 4\pi\vec{\chi}$. Here $\vec{\chi}$ is the magnetic susceptibility tensor. There are two approaches to the calculation of these parameters in anisotropic magnetic materials, both based on solution of the Landau–Lifshitz equation of motion of the magnetization vector [1]. The first — the method of effective demagnetization factors — was proposed by Kittel [2] and further developed by Macdonald [3]. It is based on a solution of the equation of motion in a specially chosen Cartesian coordinate system (CS), one of the axes of which it is directed alone the equilibrium direction of the magnetization vector. The second and more general approach: the Smit-Suhl method — was developed in the works of Smit, Beljers [4], and Suhl [5]. In it the equation of motion is solved in an arbitrary spherical coordinate system.

In work [6], using a method analogous to the Smit–Suhl method, we calculate the components of the magnetic susceptibility tensor in anisotropic materials with anisotropic magnetomechanical ratio. The aim of this work is to analyze derived in [6] formulas for a composite material consisting of randomly oriented magnetic particles of ellipsoidal shape with uniaxial magnetic anisotropy.

II. Main Part

We consider a sample in the shape of an ellipsoid of revolution. We assume that the axis of rotation of the ellipsoid coincides with the hexagonal axis of the crystal. As a rule, in a ferromagnetic with hexagonal crystal structure the magnitude of the crystallographic anisotropy in the basis plane is small [7] and in the majority of practical situations can be neglected. The expression for the total energy of such crystals is written as

$$U = M_0 H_0 \cos(\Theta - \vartheta) + 2\pi M_0^2 (N_\perp - N_\parallel)\sin^2\vartheta + k_1 \sin^2\vartheta. \quad (1)$$

Here k_1 are the constants of magnetocrystalline anisotropy, $N_\perp, N_\parallel$ are the demagnetizing factors of the sample, where $2N_\perp + N_\parallel = 1$. When recording of the formula (1) is considered that the problem has a cylindrical symmetry and vectors of the magnetizing field $\vec{H}_0(\Theta,\Phi)$ and magnetization $\vec{M}(\vartheta,\varphi)$ are arranged in one plane. The transcendental equation for calculating of equilibrium angle ϑ_0 is written in the form:

$$H_0 \sin(\Theta - \vartheta_0) + (1/2)\sin 2\vartheta_0 H'_{a1} = 0\,. \quad (2)$$

Here $H'_{a1} = 2k_1/M_0 - 4\pi M_S\left(N_\parallel - N_\perp\right)$. We introduce the following notation:

$$\Omega_1 = \gamma[H_0\cos(\Theta - \vartheta_0) + H'_{a1}\cos(2\vartheta'_0), \Omega_2 = \gamma H_0 \sin\Theta / \sin\vartheta_0\,,$$

$$Zn = \omega_0^2 - (1+\alpha^2)\omega^2 + i2\omega\omega_r\,,$$

$$\omega_0^2 = \Omega_1\Omega_2\,,\ \omega_r = (1/2)\alpha(\Omega_1 + \Omega_2).$$

Here α — damping constant in the Landau-Lifshitz-Gilbert equation. The expressions for the components of the tensor $\vec{\chi}^H$ in the laboratory coordinate system (1, 2, 3), where axis 3 coincides with the direction of the applied static magnetizing field $\vec{H}_0$, in this notation are written as follows:

$$\begin{aligned}
\chi_{11}^H &= \left(\gamma M_S / Zn\right)(\Omega_1 + i\omega\alpha),\\
\chi_{22}^{MH} &= \left(\gamma M_S / Zn\right)(\Omega_2 + i\omega\alpha)\cos^2(\Theta - \vartheta_0),\\
\chi_{33}^H &= \left(\gamma M_S / Zn\right)(\Omega_2 + i\omega\alpha)\sin^2(\Theta - \vartheta_0),\\
\chi_{12(21)}^H &= \pm i\omega\left(\gamma M_S / Zn\right)\cos(\Theta - \vartheta_0),\\
\chi_{13(31)}^H &= \pm i\omega\left(\gamma M_S / Zn\right)\sin(\Theta - \vartheta_0),\\
\chi_{23(32)}^H &= \left(\gamma M_S / Zn\right)(1/2)(\Omega_2 + i\omega\alpha)\sin 2(\Theta - \vartheta_0).
\end{aligned} \quad (3)$$

To calculate susceptibility tensor of a composite medium with arbitrarily oriented ferrite particles, the independent-grains approximation, developed by Schlömann, is used [8]. The components of the magnet-

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ic susceptibility tensor can be obtained by averaging the corresponding components of the tensor for a monocrystalline grain (3) over all possible orientations of the magnetizing field $\vec{H}_0(\Theta,\Phi)$. Averaging of the components of the tensor $\ddot{\chi}^H$ over the azimuthal angle Φ can be done analytically since the problem has cylindrical symmetry. The averaged tensor components $\langle\ddot{\chi}^H\rangle_\Phi$ are written as:

$$\begin{aligned}&\chi_{1'1'}=\chi_{2'2'}=0.5(\chi_{11}^H+\chi_{22}^H),\ \chi_{3'3'}=\chi_{33}^H,\\&\chi_{1'2'(2'1')}=\chi_{12(21)}^H,\ \chi_{1'3'(3'1')}=\chi_{2'3'(3'2')}=0.\end{aligned}\qquad(4)$$

Averaging expressions (4) over the polar angle Θ were done numerically for a fixed value of the frequency of the variable field ω and a given set of values of the magnetizing fields $H_{min} \le H_{0i} \le H_{max}$. A grid of equilibrium angles $\vartheta_0(H_{0i},\Theta_j)$ was constructed by varying the angle Θ from 90 to 0.01° with a step of 0.01° and solving Eq. (2). Next components of tensor (4) were calculated and numerically integrated over Θ. As a result, we obtain the field dependences of the components of the tensor of the composite material $\chi_\perp = 0.5c_M\langle(\chi_{11}^H+\chi_{22}^H)\rangle_\Theta$, $\chi_\parallel = c_M\langle\chi_{33}^H\rangle_\Theta$, $\pm i\chi_a = c_M\langle\chi_{12(21)}^H\rangle_\Theta$ for the given frequency, where c_M is the particle concentration in the composite. Results of calculations for a frequency of 40 GHz are presented in Figs. 1 and 2 for the following parameters: $\gamma/2\pi = 2.8$ GHz/kOe, M_0=300 Gs, c_M = 1, α = 0.05, anisotropy fields H'_{a1} = 10 kOe (Fig. 1, ferrite particles have an easy magnetization axis (EMA)) and H'_{a1} = –10 kOe (ferrite particles have an easy magnetization plane (EMP)).

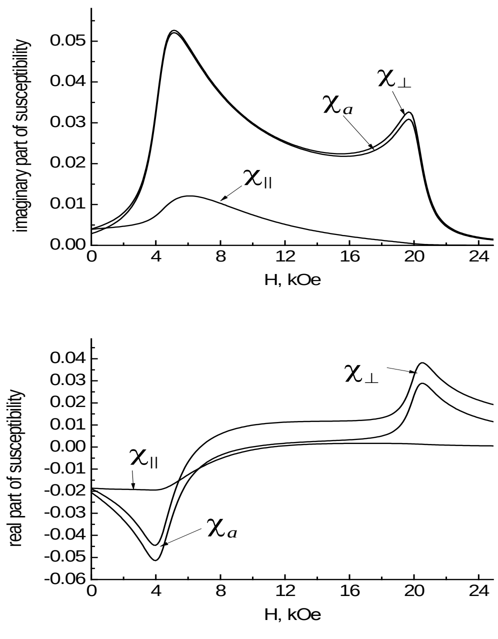

Fig. 1. Tensor components for a material with an EMA.

Рис. 1. Компоненты тензора материала с ОЛН

According to Figs. 1 and 2, near the field respective resonance fields along the easy and hard directions of magnetization the following peculiarities are observed in the field dependences: maxima and steps. The magnitude of the longitudinal component of the susceptibility of materials with an EMP is substantially lower than for materials with an EMA.

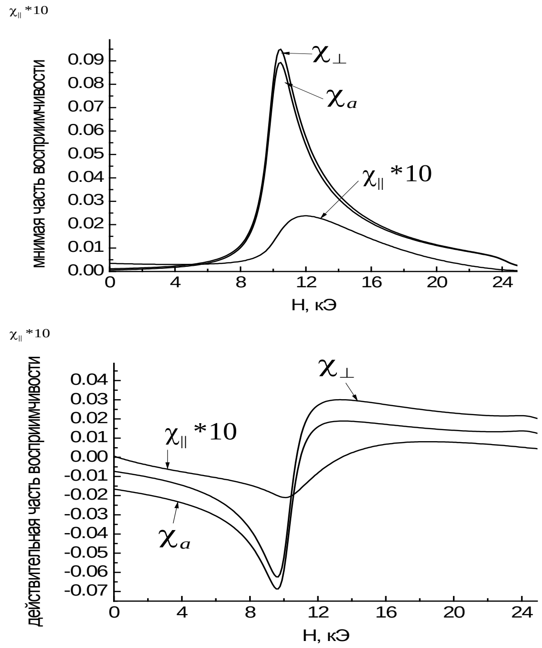

Fig. 2. Tensor components for a material with an EMP.

Рис. 2. Компоненты тензора материала с ПЛН

III. Conclusion

In summary, we have obtained the tensor $\ddot{\chi}^H$ of magnetic particles of ellipsoidal shape with uniaxial magnetic anisotropy in the laboratory coordinate system. Then we calculate susceptibility tensor of a macroscopically isotropic composite medium containing ferrite particles with uniaxial magnetic anisotropy. This tensor contains only diagonal $\chi_\perp$, $\chi_\parallel$ and antisymmetric $\pm i\chi_a$ components, which corresponds to generally accepted notions about an isotropic magnetized medium [1].

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