On the theory of domain boundary motion in a magnetic field

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The magnetic-dipole radiation of electromagnetic waves, which is associated with domain boundary motion in a magnetic material and which arises in those cases when magnetization precession occurs due to boundary motion, is examined.

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It is known that under certain conditions magnetization precession occurs at a moving domain boundary.[1-3] It is natural that such precession should be accompanied by magnetic-dipole radiation of electromagnetic waves, whose examination is the subject of this paper. In order to explain that basic features of this phenomenon, let us examine the simplest situation. We shall analyze a uniaxial ferromagnet in an external field H_z directed along the easy axis of magnetization (the z axis). It is known that the Landau-Lifshitz equation allow an exact solution describing the motion of a domain boundary perpendicular to the easy axis of magnetization.[3] Such domain boundaries (head-to-head walls) are charged, they can sometimes be observed experimentally, and they can be produced by means of an appropriate inhomogeneous magnetic field.

We shall represent the magnetization in the form

$$M_x = M_s \sin\theta\cos\phi\,, \quad M_y = M_s \sin\theta\sin\phi\,, \quad M_z = M_s \cos\theta, \tag{1}$$

where M_s is the saturation magnetization, and the polar angle θ is measured from the z axis. The solution of the Landau-Lifshitz equation, which describes the domain boundary examined above, has the form[3]:

$$\cos\theta = \tanh\frac{z}{\Delta}\,, \quad \sin\theta = \cosh^{-1}\frac{z}{\Delta}\,, \quad \frac{d\theta}{dz} = \frac{1}{\Delta}\sin\theta\,, \tag{2}$$

$$z = z - q(t)\,, \quad \Delta = (A/(K - 2\pi M_s^2))^{1/2}, \tag{3}$$

$$\phi = (1 + a^2)^{-1}\gamma H_z(t)\,, \tag{4}$$

$$q = (1 + a^2)^{-1} a\Delta\gamma H_z(t)\,, \tag{5}$$

where K is the uniaxial anisotropy constant $|K > 2\pi M_s^2|$, A is the exchange stiffness contant, and α is the Hilbert damping constant. Equation (4) describes the uniform spin precession due to boundary motion.

Let us calculate the electromagnetic field produced by such precession for the natural condition $\lambda \gg a$, where λ is the wavelength of the field and a is the maximum dimension in the plane of the domain boundary. In this case, according to Ref. 4, the vector potential **A** in the wave zone is defined by the formula (in standard notations):

$$\mathbf{A} = \frac{1}{cR_0}[\dot{\mathbf{m}}, \mathbf{n}], \tag{6}$$

in which

$$m_x = M_s \int dV \sin\theta \cos\phi = M_s \cos\phi(t) S \int_{-\infty}^{\infty} dz \sin\theta(z-q)$$

$$= M_s S \pi \Delta \cos\phi(t) = m_0 \cos\phi(t)$$

$$m_y = m_0 \sin\phi(t), \quad m_z = 0 \tag{7}$$

$$m_0 = M_s S \Delta \pi,$$

where S is the area of the domain boundary.

The fields **E** and **H** are

$$\mathbf{E} = \frac{1}{c^2 R_0}[\mathbf{n}, \ddot{\mathbf{m}}], \quad \mathbf{H} = \frac{1}{c^2 R_0}[[\ddot{\mathbf{m}}, \mathbf{n}], \mathbf{n}]. \tag{8}$$

At $H_z = \text{const}$ the radiation is monochromatic at the frequency $\Omega = \gamma H_z$. Using Eqs. (4), (7), and (8) and the standard formulas for classical radiation theory,[4] we obtain the angular distribution (averaged over the precession period) of the radiation intensity:

$$dI = \frac{m_0^2 \Omega^4}{8\pi c^3}(1 + \cos^2\psi)\, d\omega, \tag{9}$$

where ψ is the angle between the easy axis of magnetization and the observation direction **n** and $d\omega$ is a solid angle element [1)]. The total radiation intensity is

$$I = 2m_0^2 \Omega^4 / 3c^3. \tag{10}$$

The radiation polarization is defined by the vector $[\ddot{\mathbf{m}} \times \mathbf{n}] = \Omega^2[\mathbf{n} \times \mathbf{m}]$. $\psi = 0$ the polarization is circular, whereas at $\psi = \pi/2$ it is linear (along the z axis); in the general case it is elliptical with a semiaxis ratio equal to $\cos\psi$. Estimates show that for reasonable values of the parameters (M_s, H_z, K, S) the radiation intensity I is completely adequate to be detected experimentally.

We examined a domain boundary motion along the easy axis of magnetization. The magnetization precession can also occur as a result of domain boundary motion in a perpendicular plane to the axis. Here, however, the situation is more complicated. In particular, the magnetization precession, and hence the radiation of electromagnetic waves, appears on condition that the external field exceeds some critical value. In fact, it is known[5] that at $H_z < \alpha 2\pi M_s$ a solution of the Landau-Lifshitz equation that describes the steady-state motion of the domain boundary with $\phi = \text{const}$ (Walker solution). Such motion has no electromagnetic radiation. At $H_z > \alpha 2\pi M_s$, according to Refs. 1, 2, the domain boundary motion is oscillatory in nature and is accompanied by magnetization precession; the radiation in this case is not monochromatic. The magnetization precession is described adequately by Eq. (4) only when $H_z \gg \alpha 2\pi M_s$ and $K \gg 2\pi M_s^2$, and for this case Eqs. (8)–(10) given above are valid. Despite the large number of theoretical papers in which domain boundary motion, accompanied by magnetization precession, has been investigated, up to now there have been no direct experiments to observe the precession. The observation of the magnetic-dipole radiation can be such an experiment. The precession can be "reconstructed" from its angular and frequency dependence.

[1)] A similar formula was given in Ref. 4 for the electromagnetic radiation of a rotator or symmetrical top that has an electric dipole moment.

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