Research articles

Dynamics of the magnetic nanoparticles lattice in an external magnetic field

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ABSTRACT

In this paper the processes of quasi-static and dynamic magnetization reversal are studied for square lattices of magnetic nanodipoles with cubic crystallographic anisotropy. The response of the total magnetic moment to the magnetic field pulse of different duration and polarization is determined for different orientational configurations of dipoles. The oscillation modes of the total magnetic moment under alternating magnetic field are also investigated. Regular, quasiperiodic and chaotic oscillatory regimes have been found. The conditions under which oscillations propagate from individual dipoles to the whole system have been revealed.

1. Introduction

In recent years, the magnetic superstructures and ensembles of magnetic particles created by nanotechnologies have been extensively studied [1–7]. Among this kind of structures, two-dimensional magnetically ordered structures consisting of single-domain nanoparticles formed, for example, on the basis of ferromagnetic metals, are of special interest [8]. The main contribution to the interaction of magnetic moments in such lattices is made by dipole-dipole interaction [8,9]. In [10–13], equilibrium states and dynamic regimes arising in the process of magnetization reversal of linear chains and square lattices of nanoparticles in an external static magnetic field are reviewed. Discrete structures lead to significant differences of equilibrium states and dynamic regimes, occurring during the magnetization reversal of linear chains and square lattices of nanoparticles, from the properties of monodomain macroscopic objects. Such differences, in particular, include bistable states of the lattices due to the presence of different orientational configurations with an unequal total magnetic moment, as well as possible controlled transitions between configurations and dynamic oscillatory regimes of the system's magnetic moment upon their magnetization reversal [10–13].

Along with this, regular ensembles of magnetic nanoparticles with various dimensions can serve as a medium for super-dense recording and storage of information. The possibility of recording information on the magnetic dipoles lattice is based on a change in the equilibrium configuration of the magnetic moments under radio pulses of the magnetic field, and the reading is ensured by excitation of the resulting configuration through a low-power radio pulse at the frequency of ferromagnetic resonance and by scanning the frequency of the dipole system response [14–16].

In this paper, static and dynamic regimes of plane lattices consisting of dipole-interacting single-domain magnetic nanoparticles with cubic crystallographic anisotropy are investigated. Possible equilibrium configurations of the lattices, features of the response of the total magnetic moment to the external magnetic field pulse and vibrational regimes caused by an alternating field are reviewed. Specific attention is paid to the study of the dynamics of dipole lattices with parameters corresponding to the state near the stable equilibrium boundary. The processes of chaotic oscillations propagation from edge dipoles to the entire system, as well as the processes of individual dipoles reorientation under an external pulse are studied. A comparison is made of the response of the dipole lattice to the magnetic field pulse at various parameters of both the lattice and the active pulse.

2. Initial equations

Let us consider a square lattice of interacting spherical single-domain nanoparticles with the diameter d, the distance between the centers of the nearest dipoles a and the magnetic moment equal in magnitude $|\mathbf{m_i}| = m$ and proportional to the volume of a nanoparticle V. The energy of the i-th nanodipole can be expressed as a sum of the Zeeman energy in the external magnetic field, H, the energy of the nanoparticle cubic anisotropy and the dipole–dipole interaction energy, as follows:

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$$W_i = -\mathbf{m}_i\mathbf{H} + W_a(\mathbf{m}_i) + \sum_n W_d(\mathbf{m}_i,\mathbf{m}_n). \tag{1}$$

The external magnetic field is a sum of static and high-frequency fields $\mathbf{H} = \mathbf{H}_c + \mathbf{H}(t)$; and the energy of cubic anisotropy in the case when X,Y,Z are aligned along three crystallographic axes $\langle 100 \rangle$ of a nanoparticle has the following form:

$$W_a = \frac{VK_1}{m^4}(m_{ix}^2 m_{iy}^2 + m_{iy}^2 m_{iz}^2 + m_{iz}^2 m_{ix}^2), \tag{2}$$

where K_1 is the cubic anisotropy constant of the nanoparticle material. Let us consider the X axis as perpendicular to the lattice plane and the other two axes as parallel to the lattice sides. The dipole-dipole interaction energy is expressed as follows:

$$W_d(m_i) = \sum_{n \neq i}\left(\frac{m_i m_n r_{in}^2 - 3(m_i r_{in})(m_n r_{in})}{r_{in}^5} \right), \tag{3}$$

where $\mathbf{r}_{in}$ and r_{in} are the radius-vector and the distance between the i-th and the n-th dipoles. The dynamics of each of the magnetic moments is described by the Landau–Lifshitz equation with the relaxation term in the Hilbert form [15]:

$$\frac{\partial \mathbf{m}_i}{\partial t} = -\gamma \mathbf{m}_i \times \mathbf{H}_i^{ef} - \frac{\alpha}{m_i}\mathbf{m}_i \times \frac{\partial \mathbf{m}_i}{\partial t}, \tag{4}$$

where γ is the gyromagnetic ratio, and α is the dissipation parameter equal for all the particles. The effective magnetic field generated in the location of the i-th dipole by the rest of dipoles and by the external field $\mathbf{H}$, has the following form:

$$\mathbf{H}_i^{ef} = -\frac{\partial W_i}{\partial \mathbf{m}_i} = \mathbf{H} + \mathbf{H}_{ai} + \sum_{n \neq i}\frac{3(\mathbf{m}_n \mathbf{r}_{in})\mathbf{r}_{in} - \mathbf{m}_n r_{in}^2}{r_{in}^5}. \tag{5}$$

For the cubic anisotropy field, each of the three components ($\nu \equiv x,y,z$) is determined by the following expression:

$$H_{ai\nu} = -\frac{2VK_1}{m}\mu_{i\nu}(1-\mu_{i\nu}^2), \tag{6}$$

where $\boldsymbol{\mu}_i = \mathbf{m}_i/m$. Next, let us move to the dimensionless parameters: $\mathbf{e}_{in} = \mathbf{r}_{in}/r_{in}$, $\tau = (m\gamma/d^3)t$, $l_{in} = r_{in}/d$. In this case, Eqs. (4) and (5) take the form:

$$\frac{\partial \boldsymbol{\mu}_i}{\partial \tau} = -\boldsymbol{\mu}_i \times \mathbf{h}_i^{ef} - \alpha \boldsymbol{\mu}_i \times \frac{\partial \boldsymbol{\mu}_i}{\partial \tau}, \tag{7}$$

where

$$h_i^{ef} = h + h_{ai} + \sum_{n \neq i}\left[\frac{3(\mu_n e_{in})e_{in} - \mu_n}{l_{in}^3} \right]. \tag{8}$$

An external field is expressed as $\mathbf{h} = \mathbf{H}d^3/m$ and the cubic anisotropy field as:

$$h_{aij} = -2k_1\mu_{ij}(1-\mu_{ij}^2), \tag{9}$$

where $k_1 = K_1 V d^3/m^2$ is the dimensionless cubic anisotropy. For further analysis, the vector Eq. (7) is given with three scalar equations. Thus, for the x component, we get:

$$(1+\alpha^2)\frac{\partial \mu_{ix}}{\partial \tau} = (\mu_{iz} + \alpha\mu_{ix}\mu_{iy})h_{iy}^{ef} - (\mu_{iy} + \alpha\mu_{iz}\mu_{ix})h_{iz}^{ef} - \alpha(1-\mu_{ix}^2)h_{ix}^{ef}. \tag{10}$$

The equations for the rest of the $\partial \boldsymbol{\mu}_i/\partial \tau$ value components are of a similar form and can be obtained by the cyclic rearrangement of the x,y, and z indices.

3. Equilibrium configurations

Equilibrium orientations of the lattice's individual magnetic moments and dynamic of it's total magnetic moment were determined with due consideration of the connections between all the ensemble
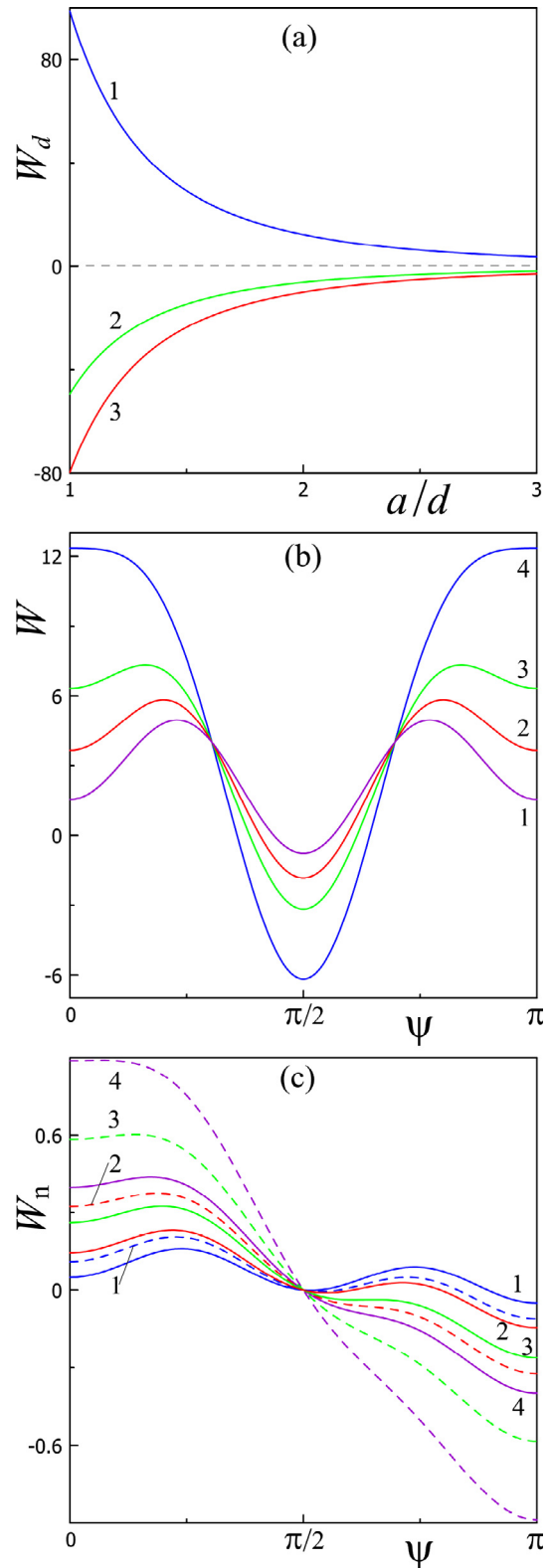

Fig. 1. Dependence of the equilibrium X and Z components (curves 1 and 2) of the total magnetic moment of the lattice on the distance between nanoparticles; in the initial state, the "internal" dipole is oriented along the X or Z axis (curves 1, 2), the remaining dipoles are along the Y axis; the configurations are given for $a/d = 2.5$ (1, 2), $a/d = 2$ (3) and $a/d = 1$ (4, 5); $k_1 = -0.5$.

elements based on the numerical solution of the above equations by the fourth-order Runge Kutta method.

In the absence of external fields, the equilibrium orientation