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Domain wall dynamics in magnetic nanotubes driven by an external magnetic field*

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We use the Landau–Lifshitz–Gilbert equation to investigate field-driven domain wall propagation in magnetic nanotubes. We find that the distortion is maximum as the time becomes infinite and the exact rigid-body solutions are obtained analytically. We also find that the velocity increases with increasing the ratio of inner radius and outer radius. That is to say, we can accelerate domain wall motion not only by increasing the magnetic field, but also by reducing the thickness of the nanotubes.

Keywords: domain wall, magnetic nanotubes, magnetic field

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1. Introduction

Owing to the tubular structure, the magnetic nanotubes have different properties compared with other nanomaterials. For magnetic nanotubes, magnetism is one of the main features and its magnetic properties can be used to record information, information transmission,[1–3] and realize logic devices.[4,5] In recent years researchers have synthesized many types of nanotubes[6–9] through continuous exploration, and often use the inside radius, outside radius, and length to describe the nanotubes. In the application of biology, both inside and outside nanotubes have strong surface activity, which can be used in other substances, adsorption in drug load, targeted therapy, and cell culture.[10] In the application of chemistry, the magnetic nanotube has a catalytic performance which is far greater than other nanoparticles. Hence, the magnetic nanotubes in catalytic chemistry have important research significance.[11]

In the research of nanomaterial magnetic problems, the domain wall (DW)[12–15] in the nanostructures plays a very important role. Most of the previous studies on DW propagation in magnetic nanostructures focused on flat strips.[16–19] A great deal of research has already been done, but most are related to one- and two-dimensional nanostructures, while the research on three dimensional nanotubes is lacking. In general, the motion of a DW can be driven by a magnetic field[19–23] or spin-polarized current.[24–27] On the flat strips, the well-known Walker breakdown of DWs[28] presents a major obstacle. Above a critical velocity, when the Walker breakdown occurs, the original DW structure collapses and it results in an abrupt drop of DW velocity. Still under discussion is whether there is an alternative to the Walker breakdown on the magnetic nanotubes. Analytic models by Landeros and coworkers predicted a decrease in velocity after a certain threshold.[29,30] Simulations by Yan *et al.* claimed the suppression of the breakdown, at least in certain geometric dimensions.[31] If this is the case, the domain wall velocities could reach the phase velocity regime, which in turn would lead to Cherenkov-like spin wave emission.[32] Magnetic nanotubes belong to a new class of interesting materials where the surface curvatures strongly influence the magnetization, thereby having a dominant effect on the magnetic response. The DW type studied here is the vortex-like DW in cylindrical nanotubes.

In the present paper, we investigate the dynamics of a DW in magnetic nanotubes under a magnetic field. We assume the magnetic manotubes to be confined within ideal cylindrical shapes, as shown in Fig. 1. First, we add a magnetic field along the z axis and establish the equation of motion of a domain wall by using the Landau–Lifshitz–Gilbert equation in magnetic nanotubes. In terms of a trial function we obtain the analytical solutions for domain-wall dynamics. Secondly, we get the domain-wall velocity, displacement, and distortion,

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which are shown as functions of time, respectively. At last, we discuss these quantities and energy variation, respectively. We find that the thickness of the nanotubes plays an important role in these quantities, such as the smaller thickness and the greater velocity of the domain wall.

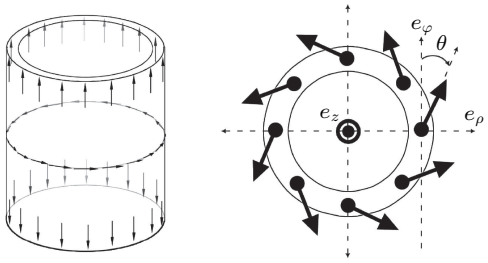


Fig. 1. Vortex-like DW and cylindrical coordinates used in the calculation.

2. Dynamics of magnetization in magnetic nanotubes

The dynamics of magnetization is described by the Landau–Lifshitz–Gilbert equation[33,34]

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\frac{\gamma}{\mu_0 M_s}\boldsymbol{m}\times\boldsymbol{H}_{\text{eff}} + \alpha\boldsymbol{m}\times\frac{\partial \boldsymbol{m}}{\partial t}, \tag{1}$$

where γ is the gyromagnetic ratio, M_s is the saturation magnetization, and α is the Gilbert damping factor. $\boldsymbol{H}_{\text{eff}} = -(\delta E/\delta \boldsymbol{m})/\mu_0$ is the effective field with E being the system energy and μ_0 being the vacuum permeability. For the magnetic nanotubes in Fig. 1 the local magnetization $\boldsymbol{m}$ takes the form $\boldsymbol{m} = \hat{e}_\rho \sin\theta\cos\varphi + \hat{e}_\varphi \sin\theta\sin\varphi + \hat{e}_z\cos\theta$, where θ represents the angle between the magnetization vector and the z axis, and φ is the out-of-plane angle of the magnetization vector projected in the φ–ρ plane. The energy function[35] of magnetic nanotubes in Fig. 1 can be written as

$$\begin{aligned} E = \int \mathrm{d}V \Bigg\{ & A\left(\frac{\partial\theta}{\partial z}\right)^2 - K\cos^2\theta - \mu_0 H\cos\theta \\ & + \left(\frac{2A\log 1/\beta}{R^2(1-\beta^2)} + \frac{A\cos^2\varphi}{l^2}\right)\sin^2\theta \Bigg\}, \end{aligned} \tag{2}$$

where A is the stiffness constant, K is the uniaxial anisotropy, β is the ratio of inner radius and outer radius, H is the applied external magnetic field along the z axis, and $R = 2l\sqrt{\log(1/\beta)/(1-\beta^2)}$ with l being the exchange length of material.

With the characteristic time $t_0 = \mu_0 M_s R^2/(\gamma A)$ and length $x_0 = \sqrt{A/(\mu_0 R^2 M_s^2)}$, we can simplify Eq. (1) into the dimensionless form

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\boldsymbol{m}\times\boldsymbol{h}_{\text{eff}} + \alpha\boldsymbol{m}\times\frac{\partial \boldsymbol{m}}{\partial t}, \tag{3}$$

where $\boldsymbol{h}_{\text{eff}} = -(\delta\varepsilon/\delta\boldsymbol{m})$ with the dimensionless energy $\varepsilon = \int \mathrm{d}z\{(\partial\theta/\partial z)^2 - \kappa\cos^2\theta + \eta(1+2\cos^2\varphi)\sin^2\theta - h\cos\theta\}$, where $\kappa = KR^2/A$, $\eta = (2\log 1/\beta)/(1-\beta^2)$, and $h = AH/(\mu_0 R^2 M_s)$. Substituting the dimensionless energy ε into Eq. (3) we obtain

$$\begin{aligned} \alpha_1\frac{\partial\theta}{\partial t} &= 2\alpha\frac{\partial^2\theta}{\partial z^2} + 2\eta\sin 2\varphi\sin\theta - \alpha h\sin\theta \\ &\quad - \alpha\left(\eta + 2\eta\cos^2\varphi + \kappa\right)\sin 2\theta, \end{aligned} \tag{4}$$

$$\begin{aligned} \alpha_1\frac{\partial\varphi}{\partial t} &= -\alpha\sin 2\varphi - 2\frac{\partial^2\theta}{\partial z^2} + h \\ &\quad + 2\left(\eta + 2\eta\cos^2\varphi + \kappa\right)\cos\theta, \end{aligned} \tag{5}$$

where $\alpha_1 = 1+\alpha^2$. With the help of Eqs. (4) and (5) we will investigate the magnetization motion in magnetic nanotubes driven by the external field.

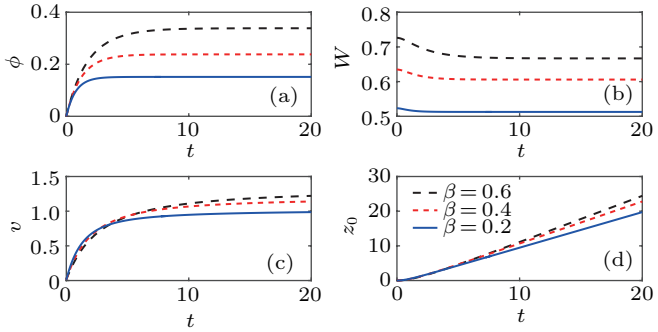


Fig. 2. (color online) The DW angle ϕ, width W, velocity V, and the displacement z_0 as a function of time t. The parameters are $\kappa = 0.3$, $\alpha = 0.1$, and $h = 0.5$.

3. Domain wall dynamics

The Walker solution analysis[36–38] has been extensively adopted to investigate the moving DW in response to a magnetic field[39–42] or spin-polarized current.[43–50] The main idea of the so-called Walker method is to simplify the DW motion into a dynamic problem described by the center position and rotation angle. Therefore, the dynamics of a single DW can be qualitatively comprehended by one-dimensional analytical models that predict a rigid-body propagation below the Walker breakdown and an oscillatory DW motion above it.[39–41] To this purpose, we follow Walker's analysis of domain-wall motion by introducing a trial function

$$\begin{aligned} \varphi &= \pi/2 + \phi(t), \\ \theta &= \arccos\tanh\left[(z - z_0(t))/W(t)\right], \end{aligned} \tag{6}$$

where we have assumed that the projection of the magnetization vector in the domain wall on the ρ–φ plane only depends on the time. The second equation in Eq. (6) shows that the domain wall motion is characterized by the variation of width $W(t)$ and the wall center with $z_0(t)$. That is to say, $\mathrm{d}z_0(t)/\mathrm{d}t$ stands for the domain wall velocity $V(t)$, and $z_0(t)$ stands for the domain wall displacement.

Substituting this trial function in Eq. (6) into Eqs. (4) and (5), we get

$$W = 1/\sqrt{\eta\left(1+2\sin^2\phi\right) + \kappa}, \tag{7}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = (h - 2\eta\alpha\sin 2\phi)/\alpha_1, \tag{8}$$

$$V = (2\eta\sin 2\phi + \alpha h)W/\alpha_1 + (z - z_0)\frac{\mathrm{d}\ln W}{\mathrm{d}t}. \tag{9}$$

The above equations are the ordinary first-order differential equations, which determine the domain-wall width and the rotation of the domain-wall plane. Equations (7)–(9) can be solved by the four-order Runge–Kutta method and the numerical results are represented in Fig. 2, where the domain-wall velocity, displacement, and distortion are shown as functions of time.

From Fig. 2(a), we observe that ϕ changes from the initial value gradually to the maximum, which is affected by the ratio of inner radius and outer radius β. When β is larger, i.e., the smaller the thickness of the nanotubes, the larger the maximum value of ϕ is. From Fig. 2(a) we find that $\mathrm{d}\phi/\mathrm{d}t = 0$ as $t \to \infty$, and the domain wall distortion is maximum. Therefore, from Eq. (8) we obtain

$$\sin 2\phi(\infty) = \frac{h}{2\alpha\eta}, \tag{10}$$

which implies the maximum reduction of the domain-wall width as

$$W(\infty)/W(0) = \sqrt{\eta + \kappa}/\sqrt{\eta + 2\eta\sin^2\phi(\infty) + \kappa}. \tag{11}$$

It denotes that the domain-wall width decreases gradually, and the smaller the thickness of the nanotubes, the greater the width of the domain wall, i.e., the smaller the distortion of the domain wall structure when the domain wall structure is stable, as shown in Fig. 2(b). We can determine the nanotubes thickness to increase the stability of domain wall motion. The above results in Eq. (11) also show that in magnetic nanotubes the domain wall width is determined by the stiffness constant, anisotropy constant, and cylindrical symmetry (inner radius and outer radius).

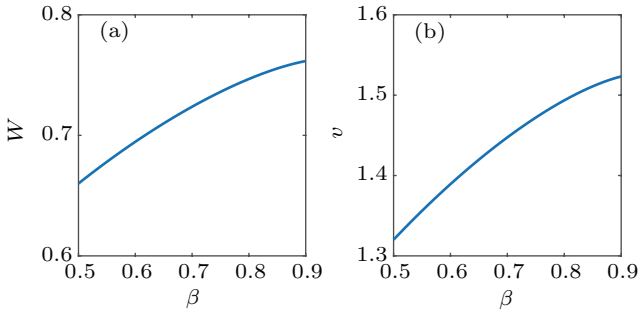


Fig. 3. (color online) The curve of domain wall width W and velocity V with the change of β. The parameters are $\kappa = 0.3$, $\alpha = 0.1$, and $h = 0.2$.

In the initial time $t = 0$, $\phi = 0$, and the initial DW velocity is zero. Under the conjunctive action of external field and damping the DW velocity attains the maximum at $t \to \infty$

$$V(\infty) = W(\infty)h/\alpha, \tag{12}$$

which is in linear proportion to the external field h. When β takes the different values, the DW velocity variation during the application of the external field is shown in Fig. 2(c). We find that when β is small, the DW velocity grows very quickly at first and the discrepancy for the different value β is very small. While the velocity with a larger β will gradually surpass that of the smaller β. When the domain wall structure is stable, the smaller the thickness of the nanotubes, the greater the velocity of domain wall. In other words, a thinner thickness of the nanotubes makes the spread of domain wall on nanotubes stronger. We also see that the DW structures in nanotubes are similar to those of flat strips, and have the significantly superior stability by reducing the thickness of the nanotubes. From Eq. (12) we can get the expression of the velocity when $t \to \infty$, and the DW velocity is proportional to the width.

We estimate this displacement by integrating the velocity

$$z_0 = \int_0^\infty V\,\mathrm{d}t = \frac{hW(\infty)}{\alpha}t. \tag{13}$$

From Fig. 2(d), we observe that the DW displacement grows continuously with time linearity. Notice that the DW displacement is inversely proportional to the damping constant and the resistance of DW displacement implies the material permeability and coercive force. Domain wall displacement resistance mainly comes from the internal stress of material internal, doping, porosity, and defects on the domain wall pinning. Under the action of the magnetic field, the domain wall can move steadily. That is to say, the magnetic field can always drive domain wall motion.

As shown in Fig. 3(a), the domain wall width becomes broadened with the increasing ratio of inner radius and outer radius β. The domain wall width is determined by the balance between the exchange interaction and anisotropy, in which the exchange interaction favors the wide width of DW, while the anisotropy tends to make the DW width narrow. That is to say, the magnetization reversal needs a smaller external energy supplement in the magnetic nanotube. From Fig. 2(b), we can find the DW width increases with the increasing ratio of inner radius and outer radius β, while the velocity increases with the increasing ratio of inner radius and outer radius β, as shown in Fig. 3(b). This means we can accelerate domain wall motion like one-dimentional nanostructure and two-dimentional nanostructures, not only by increasing the magnetic field, but also by reducing the thickness of the nanotubes.

It is interesting to study the energy variation under the field, i.e., $\mathrm{d}E/\mathrm{d}t = P_\alpha + P_\mathrm{h}$, with $P_\alpha = -h^2W(\infty)/\alpha^2$ and $P_\mathrm{h} = 0$. The first term P_α is the intrinsic damping power due to all kinds of damping mechanisms described by the phenomenological parameter. P_h is the external power. Note that the intrinsic damping power is always negative, whereas the total energy change rate is proportional to the negative DW

velocity. Thus, energy is absorbed by the external field source. If we apply a constant magnetic field, the system is under the influence of the damping effect, the energy will gradually decrease. This shows that the damping effect is dissipated energy.

4. Conclusions

In this paper, we have solved the Landau–Lifshitz–Gilbert equation with the magnetic field. We propose a trial function to analytically obtain solutions for domain-wall dynamics. Finally, the distortion is maximum and the exact rigid-body solutions are obtained analytically. The DW can achieve greater velocity in magnetic nanotubes than the rigid-body DW in ferromagnetic nanowires driven by the same magnetic field. We find the velocity becomes bigger with the increasing ratio of inner radius and outer radius. That is to say, we can accelerate domain wall motion, not only by increasing the magnetic field, but also by reducing the thickness of the nanotubes.

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