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Mechanisms of fast coherent magnetization inversion in ferronanomagnets

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ABSTRACT

Magnetic nanoparticles have a wide range of potential applications. The fast magnetization inversion is the goal of magnetic recording and other data storage, logic and communication applications operating at GHz frequencies. Here, we present theoretical studies on mechanisms of fast coherent magnetization inversion in the system of ferromagnetic nanoparticles composed of molecules or clusters with high magnetic moments. The possibilities to accelerate magnetic relaxation are considered: the feedback field from a resonator, radiation friction and Landau-Lifshitz relaxation. Equations of motion for the interparticle dipole-dipole interactions are solved numerically and the role of these relaxation mechanisms has been examined. Radiation friction is shown to be an important factor at certain conditions.

1. Introduction

Traditionally, the relaxation in a ferromagnetic system is described by Landau-Lifshitz (LL) term in the equation for a macroscopic magnetic moment [1]. Besides this, other mechanisms are possible to occur and can lead to faster relaxation and magnetization reversal than LL relaxation alone. These mechanisms are based on coherent relaxation and to study them one needs to consider the dynamics of individual magnetic moments interacting with each other in some common magnetic field.

Coherent phenomena can occur in a magnetic system when magnetic moments are in common electromagnetic field with wavelength comparable to or exceeding the size of the system. Research in this field has been started from Dicke's paper [2] on superradiation (SR), major characteristic of which is proportionality of the radiation intensity to the number of radiators squared. Later the concept of optical SR has been extended to study the coherent relaxation in magnetic systems.

In the case of ferromagnetic particles, fast inversion of the magnetic moment is the goal of magnetic recording and other data storage, logic and communication applications operating at GHz frequencies. In a medium composed of particles (magnetic centers) with large magnetic moments ($10^4 - 10^5$ Bohr magnetons), magnetization inversion can be accelerated quite substantially. In this work, we consider the interaction between ferromagnetic particles (clusters, nanoparticles) with the particle magnetic moments of the order of 10^4 Bohr magnetons. Such a large particle magnetic moment results from spins inside the nanoparticle coupled by exchange interactions.

Bloembergen and Pound [3] showed that fast magnetization reversal could be realized if a sample is coupled with a resonator electric circuit tuned to the frequency of magnetization precession. This mechanism is often called radiation damping (RD). If initially a system is in non-equilibrium state with the average magnetization slightly deflected (in classical picture) from the direction of the external constant magnetic field, then returning to the equilibrium, magnetization evolution induces an electric current in the resonator (coil) that affects the system due to generated feedback magnetic field. This field under some circumstances causes the coherence between individual magnetic moments that results in fast relaxation [4–8].

Another mechanism of relaxation is related to the radiation friction [9–12]. In the case of ferromagnetic nanoparticles, the particles in the ensemble interact mostly through dipole forces. In macroscopic terms, the motion of the magnetic moment of a crystal composed of such molecules leads to the radiation of electromagnetic waves which feedback influence creates the radiation

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friction force (Lorentz force). At low temperature, when the time of transverse relaxation T_2 (most usually due to dipole-dipole interactions) is large, contribution to the relaxation by means of the radiation friction can be substantial [9]. The process of radiation is coherent when the linear sample size is smaller than the radiation wavelength so that the phase of emitted photons is the same throughout the sample. The relaxation time due to radiation friction is determined by

$$T_R \sim \frac{c^3}{|\gamma|\omega_0^3 M}, \tag{1}$$

where $\omega_0 = |\gamma|H_0, H_0$ is the constant external magnetic field, M is the total magnetic moment of a sample, c is the speed of light, and γ is the gyromagnetic ratio. This time is obtained by the expansion of the radiation field in powers of $1/c$ [11,12]. At favorable conditions T_R can be significantly shorter than T_2. Estimations are made at the end of Section 2.

2. Equations of motion

Equations of motion for each magnetic moment of the system can be written as follows:

$$\dot{\boldsymbol{\mu}}^{(k)} = -|\gamma|\boldsymbol{\mu}^{(k)} \times \left(bfH^{(k)} + \frac{2}{3c^3}\sum_j^N \dddot{\boldsymbol{\mu}}^{(j)} \right) - \frac{\alpha|\gamma|}{\mu^{(k)}}\left(\boldsymbol{\mu}^{(k)} \times \left(\boldsymbol{\mu}^{(k)} \times \mathbf{H}^{(k)}\right)\right). \tag{2}$$

Here α is Landau-Lifshitz (LL) damping coefficient. The term with $\dddot{\boldsymbol{\mu}}$ describes electromagnetic radiation friction and appears as an expansion of retarded potential in powers of $\omega_0 V^{1/3}/c \sim V^{1/3}/\lambda$ [10,11]. The sum represents common macroscopic electromagnetic field coherently radiated by individual magnetic moments. $\mathbf{H}^{(k)}$ in Eq. (2) is the effective magnetic field that consist of the following terms:

- the constant external magnetic field H_0 along Oz axis,
- the anisotropy field $\mathbf{H}_A = (H_A/\mu)(\boldsymbol{\mu}\cdot\mathbf{n})\mathbf{n}, H_A = 2E_A/\mu$, where n is a unit vector of the easy axis that has direction of Oz axis and E_A is the particle anisotropy energy,
- the feedback field $\mathbf{H} = (H, 0, 0)$ generated by the current induced in the coil which axis is chosen along Ox axis,
- the dipolar magnetic field $\mathbf{H}_d$ caused by the interparticle dipole-dipole interactions.

Thus, the effective magnetic field acting on the kth particle is $\mathbf{H}^{(k)} = \left(H + H^k_{dx}, H^k_{dy}, H_0 + H_A + H^k_{dz}\right)$. The local dipolar field $\mathbf{H}^{(k)}_d$ at the site of kth particle with the pairwise dipole-dipole energy U_{dd} is defined as $\mathbf{H}^{(k)}_d = -\partial U_{dd}/\partial\boldsymbol{\mu}^{(k)}$, where

$$U_{dd} = \sum_{\substack{k,m\\k>m}}^N \left[\frac{\left(\boldsymbol{\mu}^{(k)}\cdot\boldsymbol{\mu}^{(m)}\right)}{r^3_{km}} - \frac{3\left(\boldsymbol{\mu}^{(k)}\cdot\mathbf{r}_{km}\right)\left(\boldsymbol{\mu}^{(m)}\cdot\mathbf{r}_{km}\right)}{r^5_{km}} \right], \tag{3}$$

$\mathbf{r}_{km}$ is the vector connecting kth and mth particles (magnetic centers) and N is the number of particles.

In order to find an expression for $\dddot{\boldsymbol{\mu}}$ we assume that the fastest motion of magnetic moments occurs around the field $(H_0 + H_A)\mathbf{n}$. Thus, taking the first derivative of Eq. (2) in the zero-th order and iterating we obtain the expression for the third derivative of the magnetic moment of kth particle:

$$\dddot{\boldsymbol{\mu}}^{(k)} = |\gamma|^3\left(H_0 + H_A\frac{\mu^{(k)}_z}{\mu}\right)^2 \boldsymbol{\mu}^{(k)} \times \left(\mathbf{H}_0 + H_A\frac{\mu^{(k)}_z}{\mu}\mathbf{n}\right). \tag{4}$$

Substituting $\dddot{\boldsymbol{\mu}}^{(k)}$ in Eq. (2) we obtain the equations of motion for the components of the magnetic moments:

$$\begin{aligned}\dot{\mu}^{(k)}_x = &-\frac{2|\gamma|^4}{3c^3}\mu^{(k)}_z\sum_j^N \mu^{(j)}_x\left(H_0 + H_A\frac{\mu^{(j)}_z}{\mu}\right)^3 - |\gamma|\left(H_0 + H_A\frac{\mu^{(k)}_z}{\mu}\right)\mu^{(k)}_y \\ &- |\gamma|\left(\mu^{(k)}_y H^{(k)}_{dz} - \mu^{(k)}_z H^{(k)}_{dy}\right) + \alpha|\gamma|(H + H_{dx})\frac{\mu^{(k)2}_y + \mu^{(k)2}_z}{\mu} \\ &- \alpha|\gamma|\left(H_0 + H_{dz} + H_A\frac{\mu^{(k)}_z}{\mu}\right)\frac{\mu^{(k)}_x\mu^{(k)}_z}{\mu} - \frac{\alpha|\gamma|H_{dy}}{\mu}\mu^{(k)}_x\mu^{(k)}_y,\end{aligned} \tag{5}$$

$$\begin{aligned}\dot{\mu}^{(k)}_y = &-\frac{2|\gamma|^4}{3c^3}\mu^{(k)}_z\sum_j^N \mu^{(j)}_y\left(H_0 + H_A\frac{\mu^{(j)}_z}{\mu}\right)^3 + |\gamma|\left(H_0 + H_A\frac{\mu^{(k)}_z}{\mu}\right)\mu^{(k)}_x \\ &- |\gamma|\mu^{(k)}_z H - |\gamma|\left(\mu^{(k)}_z H^{(k)}_{dx} - \mu^{(k)}_x H^{(k)}_{dz}\right) - \alpha|\gamma|(H + H_{dx})\frac{\mu^{(k)}_x\mu^{(k)}_y}{\mu} \\ &- \alpha|\gamma|\left(H_0 + H_{dz} + H_A\frac{\mu^{(k)}_z}{\mu}\right)\frac{\mu^{(k)}_y\mu^{(k)}_z}{\mu} + \frac{\alpha\gamma H_{dy}}{\mu}\left(\mu^{(k)2}_x + \mu^{(k)2}_z\right),\end{aligned} \tag{6}$$

$$\begin{aligned}\dot{\mu}^{(k)}_z = &\frac{2|\gamma|^4}{3c^3}\left[\mu^{(k)}_x\sum_j^N \mu^{(j)}_x\left(H_0 + H_A\frac{\mu^{(j)}_z}{\mu}\right)^3 + \mu^{(k)}_y\sum_j^N \mu^{(j)}_y\left(H_0 + H_A\frac{\mu^{(j)}_z}{\mu}\right)^3\right] \\ &+ |\gamma|\mu^{(k)}_y H - |\gamma|\left(\mu^{(k)}_x H^{(k)}_{dy} - \mu^{(k)}_y H^{(k)}_{dx}\right) - \alpha|\gamma|(H + H_{dx})\frac{\mu^{(k)}_x\mu^{(k)}_z}{\mu} \\ &+ \alpha|\gamma|\left(H_0 + H_{dz} + H_A\frac{\mu^{(k)}_z}{\mu}\right)\frac{\mu^{(k)2}_x + \mu^{(k)2}_y}{\mu} - \frac{\alpha|\gamma|H_{dy}}{\mu}\mu^{(k)}_y\mu^{(k)}_z.\end{aligned} \tag{7}$$

Let us introduce dimensionless time $\tilde{t} = \omega_d t$ and angular frequencies $\omega_H = |\gamma|H, \omega_A = |\gamma|H_A$ and $\omega_d = |\gamma|\mu/a^3$, where a is the average interparticle distance and define dimensionless parameters $p_H = \omega_H/\omega_0 = H/H_0, p_d = \omega_d/\omega_0 = \mu/a^3 H_0$ and $p_A = \omega_A/\omega_0 = H_A/H_0$.

It is important to note that the total dipolar Hamiltonian does not commute with the Zeeman Hamiltonian. However, when it is split into parts, the term that commutes with the Zeeman Hamiltonian and the total magnetic moment is called the secular term. In a strong external magnetic field, the main part of dipole interactions is its secular part and the magnitude of the total magnetic moment is practically constant (with the precision less than 0.01% in our simulations) which supports the validity of using the LL relaxation term in Eq. (2). Thus, it is convenient to write the magnetic moments in terms of unit vectors $\mathbf{e}^{(k)} = \boldsymbol{\mu}^{(k)}/\mu$. The dimensionless parameter $\xi = 1/\omega_d T_R$ shows the ratio between the radiation friction and the dipole contributions. Here $T_R = 3c^3/2|\gamma|\omega_0^3 M(0)$ is the characteristic relaxation of the radiation friction and $M(0) = \mu N$ is the total magnetic moment of the sample. With the above mentioned notations, Eqs. (5)–(7) take the following form

$$\begin{aligned}\dot{e}^{(k)}_x = &-\frac{\xi}{N}e^{(k)}_z\sum_j^N e^{(j)}_x\left(1 + p_A e^{(j)}_z\right)^3 - \left(1 + p_A e^{(k)}_z\right)e^{(k)}_y/p_d \\ &- \left(e^{(k)}_y\tilde{H}^{(k)}_{dz} - e^{(k)}_z\tilde{H}^{(k)}_{dy}\right) + \alpha\left(p_H/p_d + \tilde{H}^{(k)}_{dx}\right)\left(e^{(k)2}_y + e^{(k)2}_z\right) \\ &- \alpha\left(1/p_d + \tilde{H}^{(k)}_{dz} + p_A/p_d\,e^{(k)}_z\right)e^{(k)}_x e^{(k)}_z - \alpha\tilde{H}^{(k)}_{dy}e^{(k)}_x e^{(k)}_y,\end{aligned} \tag{8}$$

$$\begin{aligned}\dot{e}^{(k)}_y = &-\xi N e^{(k)}_z\sum_j^N e^{(j)}_y\left(1 + p_A e^{(j)}_z\right)^3 + \left(1 + p_A e^{(k)}_z\right)e^{(k)}_x/p_d \\ &- \left(e^{(k)}_z\tilde{H}^{(k)}_{dx} - e^{(k)}_x\tilde{H}^{(k)}_{dz}\right) - p_H/p_d\,e^{(k)}_z - \alpha\left(p_H/p_d + \tilde{H}^{(k)}_{dx}\right)e^{(k)}_x e^{(k)}_y \\ &- \alpha\left(1/p_d + \tilde{H}^{(k)}_{dz} + p_A/p_d\,e^{(k)}_z\right)e^{(k)}_y e^{(k)}_z + \alpha\tilde{H}^{(k)}_{dy}\left(e^{(k)2}_x + e^{(k)2}_z\right),\end{aligned} \tag{9}$$

$$\dot{e}_z^{(k)} = \frac{\xi}{N}\left[e_x^{(k)}\sum_j^N e_x^{(j)}\left(1+p_A e_z^{(j)}\right)^3 + e_y^{(k)}\sum_j^N e_y^{(j)}\left(1+p_A e_z^{(j)}\right)^3\right] + p_H/p_d e_y^{(k)} - \left(e_x^{(k)}\tilde{H}_{dy}^{(k)} - e_y^{(k)}\tilde{H}_{dx}^{(k)}\right) - \alpha\left(p_H/p_d + \tilde{H}_{dx}^{(k)}\right)e_x^{(k)}e_z^{(k)} + \alpha\left(1/p_d + p_A/p_d e_z^{(k)} + \tilde{H}_{dz}^{(k)}\right)\left(e_x^{(k)2} + e_y^{(k)2}\right) - \alpha\tilde{H}_{dy}^{(k)}e_y^{(k)}e_z^{(k)}. \quad (10)$$

In Eqs. (8)–(10) all time derivatives are taken with respect to $\tilde{t}$. The dimensionless dipole field acting on kth magnetic center is

$$H_d^{(k)}/H_0 = p_d\tilde{H}_d^{(k)}, \qquad \tilde{H}_d^{(k)} = \sum_{\substack{m=1\\ m\neq k}}^N\left[\frac{3}{\tilde{r}_{km}^5}\tilde{r}_{km}\left(e^{(m)}\tilde{r}_{km}\right) - \frac{1}{\tilde{r}_{km}^3}e^{(m)}\right] \quad (11)$$

where $\tilde{r}_{km} = r_{km}/a$ is the dimensionless coordinate of distance between the magnetic centers and a is the mean interparticle distance.

In order to get a notion of the particular situation in question, it is instructive to have some numerical estimation. Let the particles be made of a ferrite with the saturation magnetization $M_s = 400$ G and have the mean size of $d = 10$ nm. Then the particle magnetic moment is $\mu = 2\times10^{-16}$ emu, which is of about 10^4 Bohr magnetons. Assuming that the volume content of the particles in the sample is $\phi = 10\%$, for the mean interparticle distance we obtain $a \sim d/\phi^{1/3} \sim 2d$. For the magnetizing field of a strength $H_0 = 3.3\times10^4$ Oe, the Larmor frequency is $\omega_0 \sim 6\times10^{11}$ Hz, whereas for the dipolar field parameter one gets $p_d = \mu/a^3H_0 \sim 10^{-3}$. To estimate the radiation friction contribution, let us take the sample volume of $V = 10^{-3}$ cm^3, which gives the number of particles: $N \sim V\phi/d^3 \sim 10^{14}$. According to formula (1) we have the characteristic time of the radiation friction $T_R = c^3/\omega_0^3\gamma\mu N \sim 3.5\times10^{-10}$ s. Then, the ratio between the radiation friction and the dipolar contributions is $\xi = 1/\omega_d T_R \sim 5$ with $\omega_d = p_d\omega_0 \sim 6\times10^8$ Hz. Thus, the radiation friction field can be larger than the dipolar field and can lead to the relaxation at favorable conditions.

On the microscopic scale, the field of the radiation friction is negligible compared to the dipolar field. If we let M in Eq. (1) to be the magnetic moment of one particle then $T_R \to \infty$, according to equation (1). Even for $M = 10^5\mu_B$, we have $T_R \sim 10^4$ s for the parameters considered above. Time T_R can be of the order of or even smaller than time T_d only when M is considered to be the macroscopic magnetic moment of the sample in Eq. (1)M can remain large during the coherent relaxation caused, for instance, by the feedback field from the resonator.

3. The feedback field equation

Considering the resonator as a LCR circuit, electric current in the circuit changes in time due to the variations of the magnetic moment of the system. It obeys the following equation [5]

$$L\frac{dI}{dt} + RI + \frac{1}{C}\int_0^t I(t\prime)dt\prime = -\frac{d\Phi}{dt}, \quad (12)$$

where $\Phi = \frac{4\pi}{c}n\eta A m_x$ is the magnetic flux in a coil with n turns and the cross-section area A, $\eta = V/V_c$ is the coil filling factor (V is the volume of the sample, V_c is the inner volume of the coil), $m = M/V$ is magnetization. The self-induction coefficient of a coil of length l is $L = 4\pi n^2A/lc^2$. The induced current generates the magnetic (feedback) field in the coil

$$H = \frac{4\pi n}{cl}I. \quad (13)$$

After taking time derivative of Eq. (12) with respect to $\tilde{t}$, replacing the current I by the magnetic field H according to Eq. (13), and using parameter p_H, we obtain the equation for the feedback field as:

$$\frac{d^2p_H}{d\tilde{t}^2} + \frac{\omega_r}{\omega_0}\frac{1}{Q\,p_d}\frac{dp_H}{d\tilde{t}} + \left(\frac{\omega_r}{\omega_0}\right)^2\frac{p_H}{p_d^2} = -4\pi\beta\left(\frac{1}{N}\frac{d^2}{d\tilde{t}^2}\sum_{l=1}^N e_x^{(l)}\right). \quad (14)$$

Let us express the coefficients in the Eq. (14) in terms of the LCR circuit (resonator) parameters: $2\gamma_r = R/L = \omega_r/Q, \omega_r = 1/\sqrt{LC}$, where Q is the quality factor, ω_r is the resonator natural frequency. The coefficient β

$$\beta = \eta N\mu/(VH_0) \quad (15)$$

defines the intensity of the coupling of magnetic moments with the coil. Using the estimation for the interparticle distance $a \approx (V/N)^{1/3}$ and the definition of the parameter $p_d = \mu/a^3H_0$, the parameter β can be represented as ηp_d.

The feedback field increases slowly as soon as the system of magnetic moments, which are initially in non-equilibrium state, begins its transition to the equilibrium state. The field reaches maximum value when z-component of the total magnetic moment passes through the zero value. The feedback field results in coherence in the system, which is a collective phenomenon as it includes contributions from each individual magnetic moment. This leads to significant acceleration of the relaxation (ideally N times). In contrast to the dipolar interactions, which lead to the disordering of individual magnetic moments, the passive resonator and the radiation friction result in their collective relaxation from the non-equilibrium to equilibrium state.

4. Results and discussion

In the Figs. 1–5, the evolution of the z-component of the net polarization $e_z(t) = \frac{1}{N}\sum_k e_z^{(k)}(t)$ is presented for different relaxation parameters. Eqs. (8)–(10) and (14) were solved numerically for fixed number $N = 10\times10\times10 = 1000$ of magnetic moments (nanoparticles). Initial values of polarization and magnetic field are taken to be $e_z(0) = -0.95, p_H = 0, \dot{p}_H = 0$. The deviation of the initial state from the exact orientational opposition to the imposed field is essential since the simulation scheme needs the "seeding" torque to set the magnetic moments into motion. Parameter of the dipolar interaction p_d is set to a typical value of 0.001 and the quality factor Q is 10 for all figures, if not noted otherwise.

First, we consider the case with no resonator ($\beta = 0$) and negligible LL relaxation ($\alpha = 0$), i.e. the relaxation is governed only by the radiation friction. Anisotropy field at a moment is also absent ($p_A = 0$). Results of the numerical simulation are presented in Fig. 1. The z-component of the total magnetic moment flips during the time of few ω_d^{-1} (which is the characteristic dipole time). As the contribution from the radiation friction increases (i.e. parameter increases) the characteristic time of the inversion decreases. Thus,

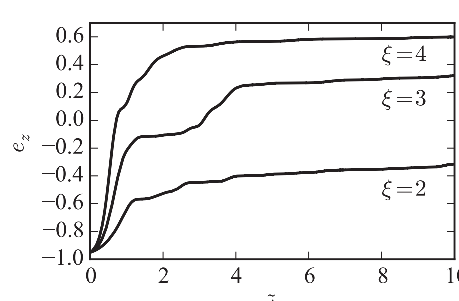

Fig. 1. Time evolution of the z-component of the total magnetic moment e_z under influence of the radiation friction alone for three values of ξ.

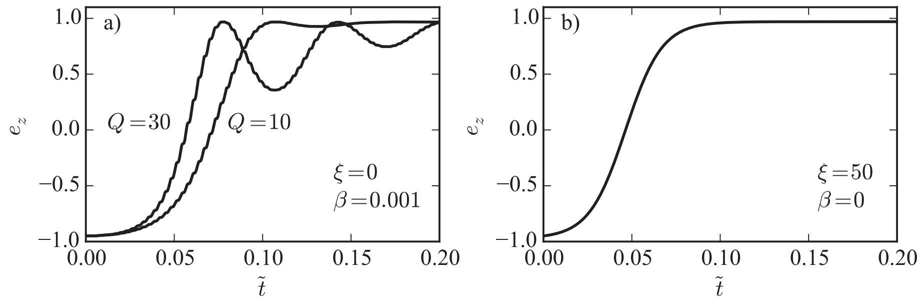

Fig. 2. Magnetization reversal caused by a) the passive resonator for $\xi = 0$, $\beta = 0.001$, b) the radiation friction for $\xi = 50$, $Q = 10$.

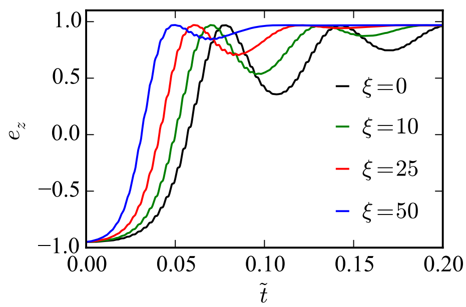

Fig. 3. Effect of the radiation friction on the time evolution of z-component of the total magnetic moment in the presence of passive resonator for $\beta = 0.001$, $Q = 30$.

we can see that the radiation friction when it is comparable with the magnitude of dipole interactions can cause magnetization flip. However, as seen in Fig. 1, the z-component of the total magnetic moment does not reach unity. This can be explained as follows. The only relaxation mechanism that preserves the magnitude of the magnetization is the Landau-Lifshits mechanism. Other mechanisms do not. The total dipolar Hamiltonian (its non-secular part) does not commute with the Zeeman Hamiltonian and this is why the z-component of total magnetization can deviate from unity when dipole-dipole interactions are strong enough. It means that Zeeman energy is not strictly conserved, part of it goes to the

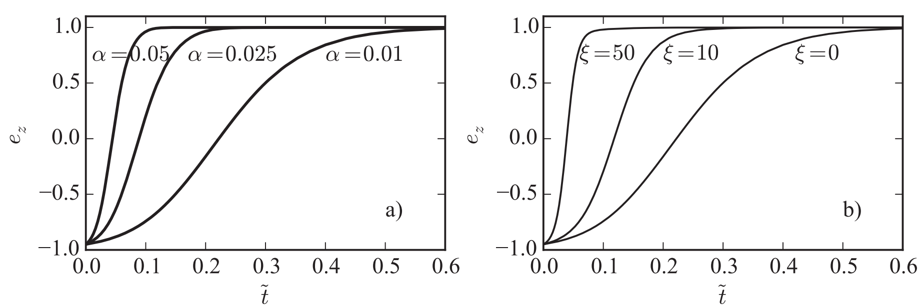

Fig. 4. Time evolution of the z-component of the total magnetic moment for a) the Landau-Lifshitz relaxation, $\xi = 0, \beta = 0, p_d = 0.001$ and b) the radiation friction and the Landau-Lifshitz relaxation, $\alpha = 0.01$, $\beta = 0, p_d = 0.001$.

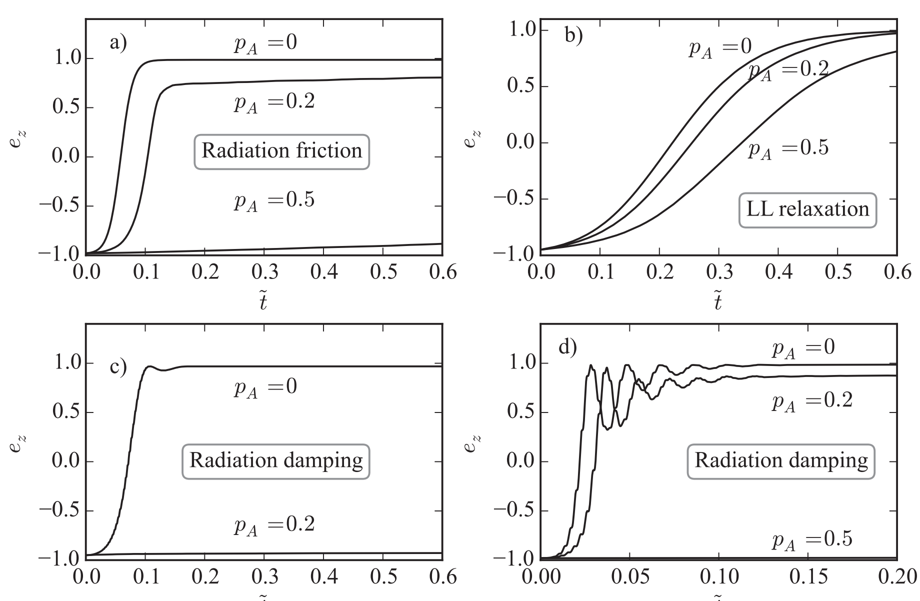

Fig. 5. Effect of the anisotropy on a) the radiation friction mechanism, $\xi = 50$, $\alpha = 0$, $\beta = 0$, b) the LL mechanism, $\xi = 0$, $\alpha = 0.01$, $\beta = 0$, c) the radiation damping mechanism; $\xi = 0$, $\alpha = 0$, $\beta = 0.001$, d) $\xi = 0$, $\alpha = 0$, $\beta = 0.01$.

dipole system. The radiation friction also doesn't conserve Zeeman energy by dissipating it into the dipole reservoir (dipole energy).

When the system is placed in the passive resonator, i.e. $\beta \neq 0$, relaxation of the total magnetic moment occurs significantly faster compared to the case when it is governed only by the radiation friction. Indeed, the major difference in the relaxation regime emerges due to the presence/absence of the passive resonance circuit that envelops the system and tuned to the Larmor frequency defined by H_0. The resonator takes in all the time-changing magnetic fields generated by the turning magnetic moments and transforms those signals into a common time-dependent field. This field is a feedback agent that affects the magnetic moments motion and entails some kind of synchronization in the assembly. The effect of the radiation friction becomes comparable with the RD effect for values of parameter $\xi \geqslant 50$ as shown in Fig. 2.

Fig. 3 shows the radiation friction effect on the evolution of the total magnetic moment in the presence of the resonator. Clearly, the reversal of the total magnetic moment is faster with increasing contribution of the radiation friction mechanism described by parameter ξ. In addition, oscillatory behavior of the magnetization time evolution is suppressed.

In the case of the Landau-Lifshitz mechanism, $\alpha \neq 0$, characteristic time of magnetization reversal is longer than that of the radiation damping and the radiation friction mechanisms (see Fig. 4a). For the precession damping parameter α, we take typical values in the range [0.01; 0.05]. For all simulations involving $\alpha \neq 0$ we have calculated the deviation in the magnitude of the individual and the total magnetic moments to be less than 0.01%.

As shown in Fig. 4b, the radiation friction significantly affects the time evolution of the z-component of the total magnetic moment governed by LL mechanism.

Fig. 5 shows the effect of the anisotropy field on the time evolution of the total magnetic moment governed by different mechanisms. For parameters given in Fig. 5, the radiation damping and the radiation friction mechanisms are most susceptible to the influence of the anisotropy, whereas LL mechanism is least influenced by the anisotropy. Thus, for magnetic systems with high anisotropy, the main contribution to relaxation is due to the LL mechanism.

5. Conclusion

The microscopic equations of motion with account of the radiation friction, Landau-Lifshitz relaxation, the radiation damping and the dipole-dipole interactions were formulated and numerically solved. The simulation results showed that the coupling with the passive resonator is the fastest relaxation mechanism. Whereas the radiation friction has a strong effect on the system in the presence of the passive resonator and the LL relaxation. When the radiation friction field is stronger than the local magnetic field, the radiation friction characteristic time of magnetization inversion is comparable with that of the radiation damping. For the system with high anisotropy, the main relaxation mechanism is shown to be Landau-Lifshitz relaxation whereas both the radiation friction and the radiation damping are suppressed. In light of the discussed mechanisms, we showed that all relaxation processes can play an important role in the fast coherent magnetization inversion.

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