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# STOCHASTIC DYNAMICS OF THE NANOPARTICLE MAGNETIZATION DRIVEN BY A CIRCULARLY POLARIZED MAGNETIC FIELD

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*The results of the numerical study of both the circularly polarized magnetic field and the thermal fluctuation influence on a uniaxial ferromagnetic nanoparticle are represented in the article. The model of such a system is based on the stochastic Landau-Lifshitz equation. The investigations are targeted at the derivation of the optimal switching parameters for the nanoparticle magnetic moment, which has two equilibrium states caused by the uniaxial anisotropy.*

***Keywords:*** *FERROMAGNETIC NANOPARTICLES, CIRCULARLY POLARIZED MAGNETIC FIELD, STOCHASTIC LANDAU-LIFSHITZ EQUATION, SWITCHING TIME.*

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## 1. INTRODUCTION

A strong increase in the interest in ferromagnetic nanoparticles (FNP) and their ensembles during the last decades is conditioned by the huge potential of their practical application. Ordered ensembles of such objects are the basis of promising devices of electronics and spintronics, among them one should note new high-density storage media (more than 1 TB/cm$^2$, or the so-called bit patterned media [1-4]), MRAM [4], etc. The possibility of FNP control using magnetic field under the condition of nanoparticle functionalization by the deposition on its surface of the coating with certain physical and chemical properties opens a new class of biotechnologies, as well as the therapy and diagnostics methods in medicine [5-8]. Now FNP become more and more important in sensor technology. Thus, the presence of FNP in the studied medium allows to significantly increase the possibilities of the magnetic resonance method when investigating the living tissues (the so-called MRI-enhancement) [5-7]. Due to the giant magnetoresistance effect, complex nanoparticles can be the basis of supersensitive magnetic gauges [4, 9]. Methods of detecting and separation of bacteria, viruses, organic molecules [5, 6, 10] based on the FNP use are widespread nowadays. Such methods are simultaneously highly sensitive, reliable, and low cost.

For all the above mentioned cases, magnetization is the key property of FNP, which conditions their functional purposes. In connection with this fact, two questions have the fundamental importance. The first question is connected with the response of a nanoparticle on the external magnetic fields, namely, with the nanoparticle displacement or change in its magnetization both by the magnitude and direction under the action of the external field. The second one is conditioned by the interaction between nanoparticle and thermostat and entailed with natural limit of the particle controllability.

As a number of recent theoretical and experimental results [11-16] show, the one of the effective control methods of the nanoparticle magnetization is the action of the magnetic field rotating in the plane perpendicular to the magnetic anisotropy axis. In particular, it was shown in [16] that exactly this type of the field conditions the minimal remagnetization time. The main disadvantage of the theoretical models used in the mentioned works is the neglect of thermal fluctuations, which play a significant role in the magnetic dynamics of sufficiently small FNP. The model, which takes into account the thermostat action, was proposed in [17], however, the analysis was carried out only for the limiting cases of the very large or very small frequency (in comparison with the resonance one). The present work is devoted to the numerical investigation of the nanoparticle magnetic dynamics under the action of the circularly polarized field and the random thermal field, which represents the thermostat influence, for the frequencies near the resonance ones.

## 2. DESCRIPTION OF THE MODEL

We assume that the nanoparticle magnetic moment $\mathbf{m}$ is constant in magnitude ($|\mathbf{m}| = \text{const}$), and the uniaxial magnetocrystalline anisotropy (Fig. 1) is only one type of anisotropy. Such model corresponds to the single-domain spherical FNP, whose spherical shape conditions the absence of surface anisotropy; and the magnetic moment constancy is realized due to the strong exchange interaction of the spin magnetic moments of the particle, when the model of coherent rotation [18] takes place. Then, for the case of interaction with a thermostat, dynamics of the FNP magnetic moment obeys the stochastic Landau-Lifshitz equation

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times (\mathbf{H}_{eff} + \mathbf{n}) - \frac{\lambda\gamma}{m} \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{eff}), \qquad (1)$$

where $\gamma$ ($> 0$) is the gyromagnetic ratio; $\lambda$ ($> 0$) is the dimensionless damping parameter; $\mathbf{H}_{eff} = \partial W/\partial \mathbf{m}$ is the effective magnetic field acting on $\mathbf{m}$; $W$ is the particle magnetic energy; $\mathbf{n}$ is the random magnetic field, which represents the thermostat action.

As it was noted above, as an external influence we consider the circularly polarized field of the following form:

$$\mathbf{h}(t) = h\cos(\omega t)\mathbf{e}_x + \rho h \sin(\omega t)\mathbf{e}_y, \qquad (2)$$

where $h$ and $\omega$ are the field amplitude and frequency; $\mathbf{e}_x$ and $\mathbf{e}_y$ are the unit vectors of the Cartesian coordinate system; $\rho = \pm 1$ for the left and right polarization, respectively. In this case the particle magnetic energy can be written in the form of [17]

$$W = \tfrac{1}{2} m H_a \sin^2\theta - mh \sin\theta \cos(\varphi - \rho\omega t). \qquad (3)$$

Here $\theta$ and $\varphi$ are, respectively, the polar and azimuth angles of vector $\mathbf{m}$. For the convenience of further calculations we perform the following change of variables: $\psi = \varphi - \rho\omega t$.

Under the condition $|\mathbf{m}| = \text{const}$, Eq. (1) is transformed to the system of two equations [17]

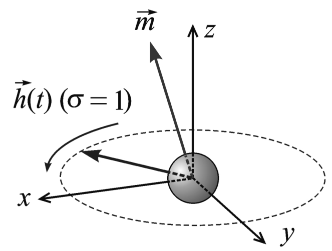



***Fig. 1** – Schematic representation of the model*

$$\begin{cases} \dot{\theta} = u(\theta,\psi) + \dfrac{\lambda}{2a}\operatorname{ctg}\theta + \sqrt{\dfrac{\lambda}{a}}\,\eta_\theta(\tau), \\ \dot{\psi} = v(\theta,\psi) - \rho\Omega + \sqrt{\dfrac{\lambda}{a}}\,\dfrac{1}{\sin\theta}\,\eta_\psi(\tau), \end{cases} \tag{4}$$

where

$$\begin{aligned} u(\theta,\psi) &= -\lambda\sin\theta\cos\theta + \tilde{h}(\lambda\cos\theta\cos\psi - \sin\psi), \\ v(\theta,\psi) &= \cos\theta - \tilde{h}\,\frac{\cos\theta\cos\psi + \lambda\sin\psi}{\sin\theta}. \end{aligned} \tag{5}$$

In the above given equations $\tilde{h} = h/H_a$ is the dimensionless amplitude of the rotating field; $\tau = \omega_r t$ is the dimensionless time; $\omega_r = \gamma H_a$ is the Larmor's frequency; $\Omega = \omega/\omega_r$ is the dimensionless frequency of the rotating field. Parameters $\eta_\theta(\tau)$ and $\eta_\psi(\tau)$ denote two independent Gaussian white noises with zero mean value and correlation function, which is proportional to the Dirac delta-function: $\langle \eta_i(\tau)\eta_j(\tau')\rangle = \delta_{ij}\delta(\tau - \tau')$, where $i, j = \theta, \psi$, $\Delta = \lambda k_B T/\gamma m$ is the noise intensity; $k_B$ is the Boltzmann constant; $T$ is the temperature.

It is reasonable to analyze the thermal effects in the nanoparticle magnetic dynamics using the ratio of the potential barrier of reorientation of the magnetic moments to the thermal energy

$$a = mH_a/2k_B T. \tag{6}$$

Since it is extremely difficult to obtain analytical solution of the system of equations (4), we should use numerical methods. The performed analysis showed that the Euler method is the optimal for the numerical solution of the system (4) among the existing methods of numerical integration of stochastic differential equations [19].

## 3. ANALYSIS OF THE RESULTS

### 3.1 Precession modes and thermal fluctuations

Deterministic magnetic dynamics of the uniaxial ferromagnetic nanoparticle under the action of the circularly polarized field is characterized by the presence of two precession modes, namely, the uniform and nonuniform ones (see, for example, [16]). The uniform mode is characterized by the constancy of the precession cone angle (Fig. 2a); while for the nonuniform mode this angle periodically changes (Fig. 2b). In the presence of thermal fluctuations, reorientation of **m** is possible even without external field. Therefore, we can speak about precession modes under the field action of the type (2) only in the restricted time intervals.

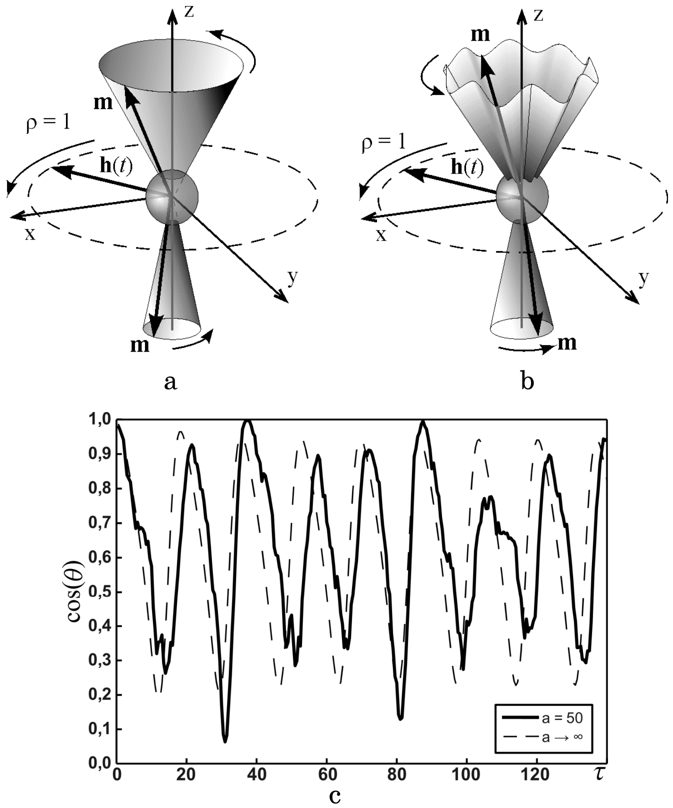



***Fig. 2*** *– Uniform (a) and nonuniform (b) precessions of the magnetic moment. Realization of the nonuniform mode for the model with thermal noise ($a = 50$) and without it ($a \to \infty$) ($\Omega = 0{,}75$, $\lambda = 0{,}2$, $\tilde{h} = 0{,}2$) (c)*

Moreover, existence of the nonuniform mode in the presence of thermostat is unobvious. And if thermal fluctuations make impossible the generation of the nonuniform precession, all peculiarities of the FNP switching process in this case [16] become not more than peculiarities of the mathematical model without noise regardless of the real physical system. The numerical simulation results show that the periodic trend is presented on the time dependence of the cosine of the precession angle (Fig. 2c) that allows to speak about the topicality of the nonuniform mode for the real situation taking into account the interaction with a thermostat.

### 3.2 Average switching time

The magnetic moment switching time from one state to another is important parameter from the practical point of view; and therefore, search of external influences, at which this quantity is the minimal one, is of a considerable importance. The problem of switching time, as a matter of fact, is the type of the problem about achievement by a random process of the specified level. However, a question what should we consider as such in the case of stochastic dynamics of the magnetic moment of the uniaxial nanoparticle, as a rule, is left open. At the same time, it is obvious that vector **m** achieves the maximum-energy state for a sufficiently long time, and then, having overcome the potential barrier, it quickly tends to a new equilibrium state. Therefore, as such specified level one can choose the position of the magnetic moment, which is deliberately far from the maximum-energy state. Found itself in such new state, magnetic moment in the future will fluctuate for a comparatively long time in the vicinity of a new equilibrium state, therefore, one can consider that the nanoparticle remagnetization process is completed. In this work we take the value of the specified level for the azimuth angle $\theta$ to be equal to $0{,}8\pi$. When modeling, we suppose that in the initial time the external field changed step-wise from zero to the given value.

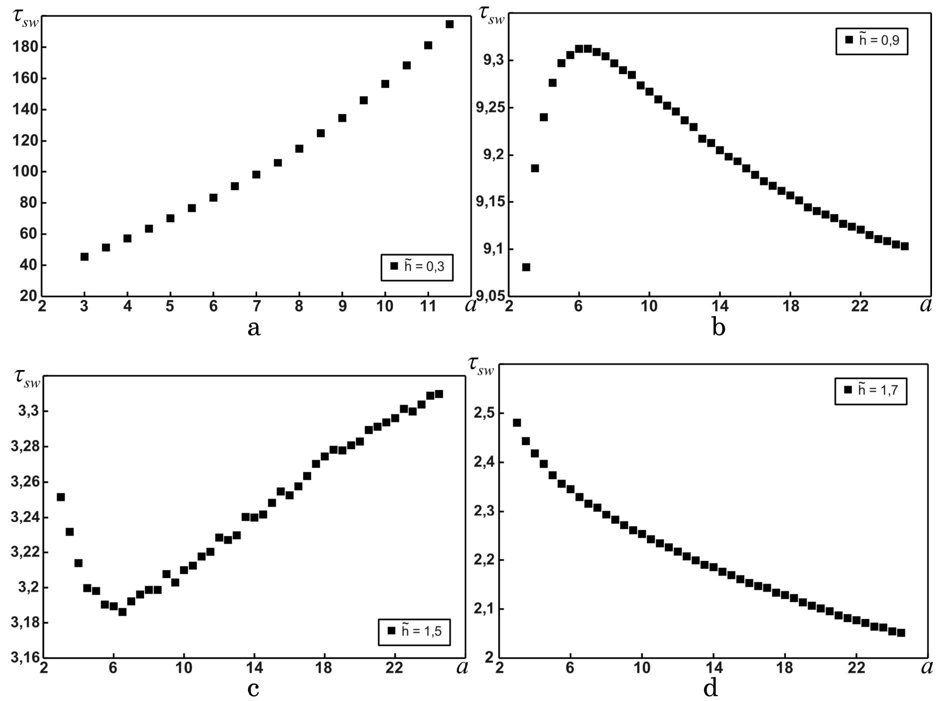



***Fig. 3*** *– Dependence of the switching time on the parameter a for different amplitudes of the rotating field: a)* $\tilde{h} = 0{,}3$ *; b)* $\tilde{h} = 0{,}9$ *; c)* $\tilde{h} = 1{,}5$ *; d)* $\tilde{h} = 1{,}7$

Obviously, thermal fluctuations can differently influence the process of the magnetic moment switching from one stable state to another depending on the relation between thermal and magnetic energies (see expression (6)). For small amplitudes of the rotating field (Fig. 3a) with the temperature growth (or with the decrease in the value of $a$) the switching time decreases. This is connected with the fact that for a small regular action, switching occurs, first of all, due to the thermal fluctuations. With the increase in the rotating field amplitude, presence of the thermal fluctuations will both prevent and promote the remagnetization process (see Fig. 3b, c) against a background of the substantial decrease in the switching time in comparison with the previous case. Here switching occurs due to the rotating field action, and thermal noise only negligibly modifies the switching time. Finally, for sufficiently large amplitudes of the rotating field, temperature increase insignificantly slows down the FNP remagnetization (Fig. 3d). All numerical results are obtained for the frequency $\Omega = 1{,}0$ and damping parameter $\lambda = 0{,}2$. Averaging was performed over $5{\cdot}10^5$ independent realizations.

Correspondingly, dependences of the switching time on the rotating field amplitude (see Fig. 4) can be conditionally classified into two types. If the rotating field amplitude is sufficiently small (for the chosen conditions of the simulation $\tilde{h}$ = 0-0,29), the value of the switching time will be comparatively large and very sensitive to the change in $\tilde{h}$ and temperature (Fig. 4a). It is obvious from Fig. 4c (see the curve $\tilde{h}$ = 0,25) that in this case rotating field cannot by itself switch the nanoparticle, and presence of fluctuations plays the fundamental role.

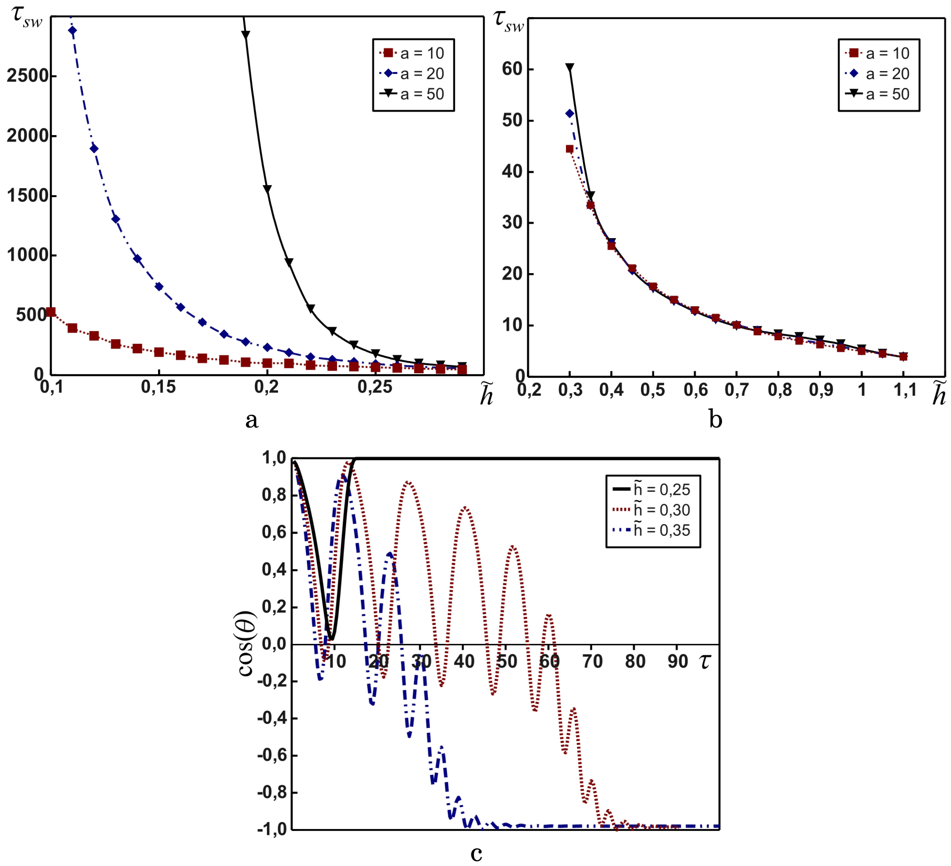


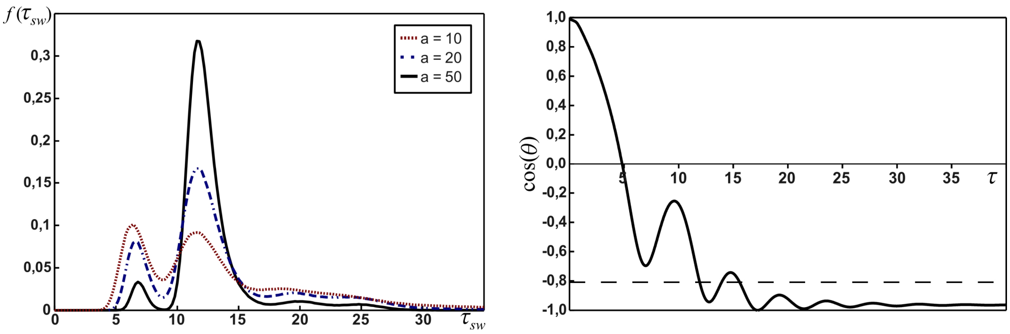

***Fig. 4*** *– Dependences of the switching time on the rotating field amplitude for different parameters a: a) small amplitudes of the rotating field; b) large amplitudes of the rotating field. c) Time dependences of cosθ of the magnetic moment for the deterministic case at different amplitudes of the rotating field*

If the field amplitude is sufficiently large to switch the magnetic moment, thermal noises slightly influence the dependence $\tau_{sw}(\tilde{h})$ (Fig. 4b). In this case the switching time is considerably less than for the previous case.

Simulation was carried out for the following parameters: $\Omega = 0{,}75$, $\lambda = 0{,}2$. Averaging was performed over 2000 independent realizations.

### 3.3 Distribution of the switching times

Since the process of FNP remagnetization has a random character, the average switching time of the magnetic moment is not self-sufficient characteristic, because switching times can be distributed differently. The performed numerical investigation showed that in the case when the rotating field amplitude is sufficiently large and the **m** reorientation is realized due to the external field, the distribution function is non-unimodal curve with some minimums and maximums (see Fig. 5a). This is connected with the fact that with the switching of the external deterministic field, due to the dynamic processes in different time moments the FNP magnetic moment is differently distant from the maximum-energy state (Fig. 5b). And in those time intervals, when **m** has the maximum energy, probability of its reorientation to a new state achieves the maximum value. In this case, the more the temperature is, the less the relative difference between minimums and maximums of the distribution is. Thus, the real switching times with almost the same probability can take the values differing a few times.




a b

***Fig. 5*** – *Distribution of the switching times ($\tilde{h} = 0,4$): a) distribution function; b) time dependence of the polar angle cosine of the magnetic moment in the deterministic case*

In the case of small field amplitudes, when switching is possible only in the presence of thermal noises, the distribution function is asymmetric unimodal curve, which decreases sufficiently weakly, that is pronounced for high temperatures (see Fig. 6a). That is, as it was expected, distribution is more "blurred". Presence of the distribution maximum is connected with the maximal deviation of **m** from the equilibrium position, as well as in the previous case.

Simulation was carried out for the following parameters: $\Omega = 0{,}5$, $\lambda = 0{,}2$. To plot each curve of the distribution, $2{,}5 \cdot 10^7$ independent realizations were performed.

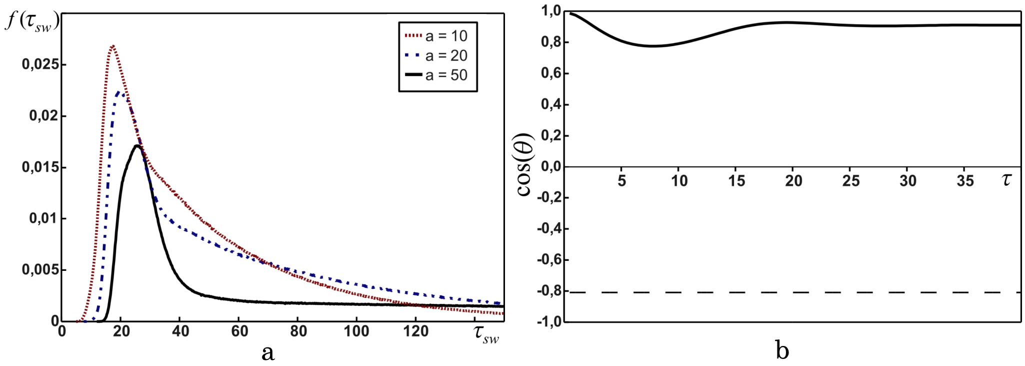



***Fig. 6*** *– Distribution of the switching times ($\tilde{h} = 0,2$): a) distribution function; b) time dependence of the polar angle cosine of the magnetic moment in the deterministic case*

## 4. CONCLUSIONS

Using the stochastic Landau-Lifshitz equation, the influence of thermal noise on the process of FNP remagnetization by the circularly polarized field, whose frequency is close to the resonance one, was numerically investigated in this work. In particular, dependences of the switching time on the temperature were obtained. As follows from these dependences, fluctuations depending on their intensity can both accelerate and slow down the magnetic moment switching between two stable states. Dependences of the switching time on the rotating field amplitude are established and analyzed as well. It is shown that for small field amplitudes the switching time strongly depends on the temperature, while for large amplitudes this dependence is very weak.

Distributions of the switching times of **m**, which can be different depending on the external field amplitudes, are obtained. It is shown that in the case when switching occurs because of the external field action, the real switching times can take values, which differ several times, with almost the same probability due to the thermal fluctuations. This information has fundamental importance for the development of new methods of magnetic recording using the circularly polarized field.

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