Minimizing The Effect Of Noise
In High-Speed Reversal Of A Magnetic Dipole

A.L. Pankratov, S.N. Vdovichev, I.M. Nefedov, and D.A. Adamchik

Institute for Physics of Microstructures of RAS, GSP-105, Nizhny Novgorod, 603950, Russia
Email: alp@ipm.sci-nnov.ru

Keywords: magnetic dipole, high-speed reversal, noise, fluctuations.

Abstract. The effect of noise on the reversal of a magnetic dipole is investigated on the basis of computer simulation of the Landau-Lifshits equation. It is demonstrated that at the reversal by the pulse with sinusoidal shape, there exists the optimal duration, which minimizes the mean reversal time (MRT) and the standard deviation (SD, jitter). Both the MRT and the jitter significantly depend on the angle $\theta$ between the reversal magnetic field and the anisotropy axis. At the optimal angle the MRT can be decreased by a factor of 7 for damping $\alpha=1$ and up to 2 orders of magnitude for $\alpha=0.01$, and the jitter can be decreased from 1 to 3 orders of magnitude in comparison with the uniaxial symmetry case. It has been demonstrated that fluctuations can not only decrease the reversal time, as it has been known before for the magnetic systems and is correct for small angles only, but it can also significantly, up to the factor of two, increase the reversal time.

Introduction

The decrease of sizes of magnetic nanoparticles used in storage media leads to the increase of fluctuations and, therefore, to increase of storage and switching errors (jitter). Theoretical investigation of noise-assisted high-speed switching of magnetic dipoles is of crucial importance both for magnetic recording media and MRAM. During past decades, in nonlinear systems driven by noise the nontrivial phenomena, such as resonant activation (RA) [1], stochastic resonance [2] and noise-delayed switching (NDS) [3] have been observed. In magnetic systems, however, the existence of only stochastic resonance effect has been confirmed [4]. Due to the complexity of the model, described by the time-dependent Landau-Lifshits equation with noise, mostly the relaxation times of magnetic dipoles have been studied [5]. Without account of noise it has been found before that there is an optimal angle between the applied magnetic field and the anisotropy axis, which is typically around 45 degrees [6]; with the decrease of the magnetic field rise time, the coercivity of magnetic particle (dynamic coercivity) increases [7]. At finite temperature the most crucial problem is the stable magnetic reversal: the remagnetization process must occur with minimal switching time and the standard deviation. It is very important for applications in storage media to investigate the RA-like effects and NDS effects, since their proper utilization can significantly improve the performance of magnetic recording devices. These effects may play positive and negative role in the accumulation of fluctuational errors in recording media: the RA phenomenon minimizes timing errors, while the NDS phenomenon increases the reversal time. The mean reversal time (MRT) of magnetic particles has been studied in [8], and it has been shown that during noise-assisted reversal the noise leads not to the increase, but to the decrease of MRT.

In the present paper the investigation of the reversal process of a magnetic dipole has been performed on the basis of computer simulation of the Landau-Lifshits equation with thermal fluctuations taken into account. It is focused on the investigation of resonant activation-like and noise delayed switching phenomena with the aim to find an optimal regime of reversal with the smallest mean reversal time and the standard deviation.
Statement of the problem and the results

The dynamics of magnetic dipole is described by the Landau-Lifshits equation:

$$\frac{dM}{dt} = -\frac{\gamma}{\beta} [M] \mathcal{H} - \frac{\alpha\gamma}{\beta M_s} [M][\mathcal{H}]$$,  

(1)

where $M$ is the magnetization of a particle, $\mathcal{H}$ is the effective magnetic field, $\gamma$ is the gyromagnetic constant, $\alpha$ is the damping, $\beta=1+\alpha^2$, $M_s = |M|$ is the saturation magnetization. The effective magnetic field contains the following components: $\mathcal{H} = \mathcal{H}_e + \mathcal{H}_T + \mathcal{H}_a$, where $\mathcal{H}_e$ is the external field, $\mathcal{H}_T$ is the fluctuational field, $\mathcal{H}_a$ is the anisotropy field. The fluctuational field is assumed to be white Gaussian noise with zero mean and the correlation function:

$$\langle H_{Ti}(t) H_{Tj}(t') \rangle = \frac{2akT}{M_s V} \delta(t-t') \delta_{ij}$$, where $k$ – Boltzmann constant, $T$ is the temperature, $V$ is the volume of the magnetic particle.

Let us consider the reversal of a magnetic dipole, initially magnetized along anisotropy axis and along $x$-axis from the state $\vec{M}(+M_s,0,0)$ to the state $\vec{M}(-M_s,0,0)$. To find the area of parameters where the fastest and the most reliable reversal occurs, as the characteristic to be studied let us choose the first passage time of a certain boundary. The mean first passage time (the mean reversal time, MRT) $\tau$, and the standard deviation of the first passage time $\sigma$ (SD, jitter) are [18]:

$$\tau = \langle t \rangle = \frac{\sum_{i}^N t_i}{N}, \quad \langle t^2 \rangle = \frac{\sum_{i}^N t_i^2}{N}, \quad \sigma = \sqrt{\langle t^2 \rangle - \langle t \rangle^2}.$$  

Here $t_i$ is the first passage time of an absorbing boundary $\vec{M}(0,M_s, M_s)$ and $N\geq10000$ is the number of realizations.

In the calculations it is convenient to use the parameters, related to the magnetic recording media [6]: $\alpha = 0.5$, $\gamma = 1.76 \times 10^7$ Hz/Oe, $M_s = 360$ emu/cm$^3$, $K = 7.2 \times 10^5$ erg/cm$^3$. The static coercivity is $H_c = 2K/M_s = 4000$ Oe. For modeling we take the amplitude of the magnetic field to be 6000 Oe. It is known that the driving by the signal with sharp fronts leads to the minimal MRT [9]. However, the pulses used in real recording media systems have finite rise time [6]. As an example of a driving with smooth fronts we consider the sinusoidal pulse $|H_e| = |H_0|\sin\pi t/t_p$ with the width $t_p$. The considered range of temperatures from 4 K to 300 K for the above listed parameters leads to the noise intensity, which is much smaller than the activation energy of the system, so at large $t_p$ the reversal occurs due to the effect of driving field. The Landau-Lifshits equation with noise has been computed both by the Heun method programmed in Fortran and by the specialized package SIMMAG, developed in the laboratory of mathematical modeling of IPM RAS.

![Fig. 1. The MRT (solid curves) and SD (dashed curves) versus pulse width for different angles between anisotropy axis and external field.](image1.png)

![Fig. 2. The MRT (solid curves) and SD (dashed curves) versus pulse width for different temperatures and $\theta=5^\circ$.](image2.png)
It is known that for zero temperature $T=0$ K the reversal of the dipole by the longitudinal field, $\theta=0^\circ$, does not occur, since the dipole is in the equilibrium state, even if this state is unstable. The presence of thermal fluctuations allows to move the dipole away from this equilibrium state. In Fig. 1 the plots of the mean reversal time (MRT) $\tau$ and the standard deviation (SD) $\sigma$ are presented for three different values of angles $\theta=0^\circ; 10^\circ; 45^\circ$ and the temperature $T=300$K. First of all, it is seen that both $\tau$ and $\sigma$ have minima as functions of the driving pulse width. This resembles the resonant activation phenomenon [1] and indicates that both these temporal characteristics can be minimized by the optimal choice of pulse duration. Similar effect has recently been observed for Josephson junctions [9]. The decrease of the MRT at large durations is due to the fact that with decrease of the width the potential barrier disappears faster. With further shortening of the pulse, the magnetization does not have enough time for the complete reversal during $t_p$, so the MRT increases. This, actually, means that for rather short pulses the transition occurs due to effect of fluctuations (the so-called noise-induced switching). The standard deviation with decrease of the pulse width behaves similarly to $\tau$. It is obvious from Fig. 1 that for $\theta=45^\circ$ the reversal is faster and more stable than for $\theta=0^\circ; 10^\circ$ at all other equal conditions. This means that the reversal process principally depends on the precession of the magnetic dipole, and can not be described by a simple two-state model. This result gives the quantitative substantiation for the idea to use the tilted magnetic field to speed up the reversal process, and also to use additional weak perpendicular magnetic field for the same purpose, which actually leads to the tilt of the aggregate magnetic field.

In Fig. 2 the MRT and SD are given for different temperatures and $\theta=5^\circ$. In spite that at large $t_p$ one can see little decrease of MRT with increase of the temperature, at small $t_p$ around minima the opposite effect of noise delayed switching (NDS) is clearly visible, quite similar to the one observed before for Josephson junctions [9], and in general case of nonlinear systems. Besides, here the SD behaves as $\sigma\sim\sqrt{T}$, see Ref. [9]. In Ref. [8] the prediction of the MRT decrease with increase of the temperature has been given. However, such behavior is observed around $\theta=0^\circ$ and is due to location of initial condition at the unstable equilibrium point, so the reversal is impossible at zero temperature and the deterministic reversal trajectory does not exist. That is why fluctuations help to leave the unstable initial state and namely this leads to the decrease of $\tau$ with increase of the temperature. For relatively large angles, the deterministic reversal trajectory do exist, which leads to the observed NDS effect: if, for example, at zero temperature the only clockwise reversal is possible at the given initial condition, at nonzero temperature due to fluctuations the dipole can sometimes be switched counterclockwise that increases the mean reversal time due to longer paths needed for the reversal in this direction.

It is interesting to study the NDS effect in more detail, plotting the minimal attainable MRT as function of temperature. The corresponding curves are presented in Fig. 3 for different values of angle between anisotropy axis and external field. It is seen that the maximal NDS effect (about two times between $T=4$K and $T=300$K) is observed at $\theta=5^\circ$ and becomes smaller and smaller with approaching the angle $\theta=45^\circ$. Therefore, the angle $\theta=45^\circ$ can also be recommended from the point of view of maximal working temperature range, which is important for certain applications.

Fig. 3. The minimal MRT versus temperature for different angles between anisotropy axis and external field.
Summary

In the present paper the effect of noise on the reversal of a magnetic dipole has been studied on the basis of computer simulation of the Landau-Lifshits equation. The interplay between resonant activation-like and noise delayed switching phenomena has been investigated. Namely, it has been demonstrated that at the reversal by the pulse with sinusoidal shape, there exists the optimal duration, which minimizes the mean reversal time (MRT) and the standard deviation (SD, jitter). Also, both the MRT and the jitter significantly depend on the angle between the reversal magnetic field and the anisotropy axis. At the optimal angle the MRT can be decreased by a factor of 7 for $\alpha =1$ and up to 2 orders of magnitude for $\alpha =0.01$; the jitter can be decreased from 1 to 3 orders of magnitude (for $\alpha$ from 1 to 0.01) in comparison with the uniaxial symmetry case. For optimal angles the SD decreases with decrease of the damping. It has been demonstrated that fluctuations can not only decrease the reversal time, as it has been known before for the magnetic systems and is correct for small angles only, but it can also significantly increase the reversal time - the effect which can be avoided by proper choice of pulse duration.

The work has been supported by RFBR-Povolzhie (project 08-02-97033).

References


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10.4028/www.scientific.net/SSP.152-153.321

DOI References