Analysis of fast precessional switching in magnetic thin films

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Abstract

The switching process of magnetic recording NiFe thin-films is considered. First, it is illustrated through numerical micromagnetic simulations that precessional switching process can be reasonably considered a quasi-uniform process, while, in conventional switching process, domain nucleation and wall motion are involved in the magnetization reversal dynamics. Second, we used analytical uniform mode theory of precessional switching to predict the duration of the applied field pulse. We verified that the uniform mode theory provide reasonably good indications on the quasi-uniform precessional switching dynamics.

The fast magnetization switching of thin films and nanoelements is one of the fundamental issues in spin dynamics studies for its importance in the area of magnetic data storage technologies. Traditionally, magnetization reversal in thin films is realized by applying a sufficiently large magnetic field almost antiparallel to the initial magnetization state and the resulting reversal dynamics is driven by dissipative precesses. Recently, the possibility of using precessional motion of magnetization to realize the switching of thin films and particles has been investigated[1,2]. In this kind of switching, the in-plane external field is approximately orthogonal to the initial magnetization state and produces a torque that drives precessional motion of magnetization; this results in a faster and less energy-consuming magnetization dynamics. Magnetization reversal is realized by switching the field off precisely when precession has brought the magnetization state close to its reversed orientation. Therefore, the applied field pulse duration has to be carefully chosen, while in conventional switching there is no such need. Although it is generally desired that thin films and nanoelements in magnetic storage devices are in almost uniform magnetization states, both conventional switching and precessional switching are nonuniform dynamic processes. In this paper, we consider the switching process of a permalloy magnetic rectangular thin-film: the thickness is c=5 nm, the major and mean edge length are respectively a=500 nm and b=250 nm. The thin-film medium has a uniaxial magneto-crystalline anisotropy whose easy axis is along the x-axis (long axis), the uniaxial anisotropy constant is $K_1=2\cdot10^3$ J/m^3 , the exchange stiffness constant is $A=1.3\cdot10^{-11}$ J/m, the saturation polarization is $J_s=1$ T ($M_s=795$ kA/m) and the damping constant is $\alpha=0.02$; the exchange length of the material is $l_{exc}=\sqrt{(2A)/(\mu_0 M_s^2)}=5.7160$ nm. We assume that magnetization dynamics of the thin-film is described by the Landau-Lifshitz-Gilbert equation, namely:

$$\frac{\partial \mathbf{M}}{\partial t}=-\gamma\mathbf{M}\times\mathbf{H}_{eff}+\frac{\alpha}{M_s}\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}\,, \tag{1}$$

where γ is the absolute value of the gyromagnetic ratio, α is the damping constant and $\mathbf{H}_{eff}$ is the effective field

$$\mathbf{H}_{eff}(\mathbf{M}(.))=\mathbf{H}_m+\mathbf{H}_{exc}+\mathbf{H}_{an}+\mathbf{H}_a\,, \tag{2}$$

which takes into account the applied field $\mathbf{H}_a$, the exchange field $\mathbf{H}_{exc}$, the anisotropy field $\mathbf{H}_{an}$ and the magnetostatic (demagnetizing) field $\mathbf{H}_m$. In micromagnetic simulations equation (1) is integrated numerically using a backward differentiation formula[3]; the spatial discretization is done using the finite element method with a mesh consisted of tetrahedrons; the mesh is finer near the corners of the thin-film (mesh edge length=5 nm < l_{exc}) where a stronger accuracy is required for the computation of magnetostatic field. A hybrid finite element boundary element method[4] is used to solve the magnetostatic problem. First, we performed micromagnetic simulations of conventional (damping)

(a) (b)

Figure 1. (a) Conventional (damping) switching process. (b) Precessional switching process

and precessional switching process for the thin-film; the external field is applied respectively antiparallel and orthogonal to the easy axis, as sketched in figure 1. We compared two aspects of the switching processes: the switching speed and the uniformity of the magnetization during the reversal process. We consider, as a measure of the switching speed, the time instant t_0 at which the average component of m_x is zero after the application of the external field (the external field strength is the same in both the simulations). In figure 2 one can observe the behavior of the average m_x component until it reaches zero, showing that the precessional switching dynamics is much faster (t_0=0.09 ns) than damping switching's (t_0=0.17 ns). This is due to the different nature of the mechanism driving magnetization motion in the two processes: in conventional switching there is only one equilibrium configuration after the application of the external field, namely the reversed state, so the switching process is a kind of relaxation process towards the equilibrium and therefore the damping process is crucial; in precessional switching the main role is played by the magnetic torque acting on the magnetization, which causes a fast precessional motion around the effective field driving the magnetization back and forth between the initial and the reversed state; in most cases this process is so fast that dissipative effects can be neglected.

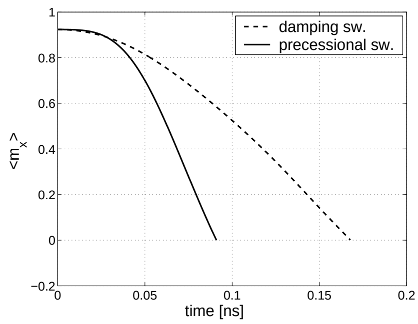


Figure 2. Numerical results. Comparison between damping (dashed line) and precessional (solid line) switching: time for average m_x component to reach zero from the starting configuration for H_a=19.51 kA/m.

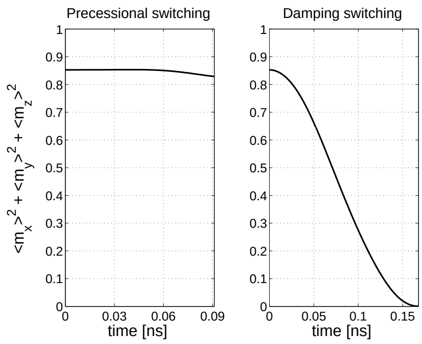
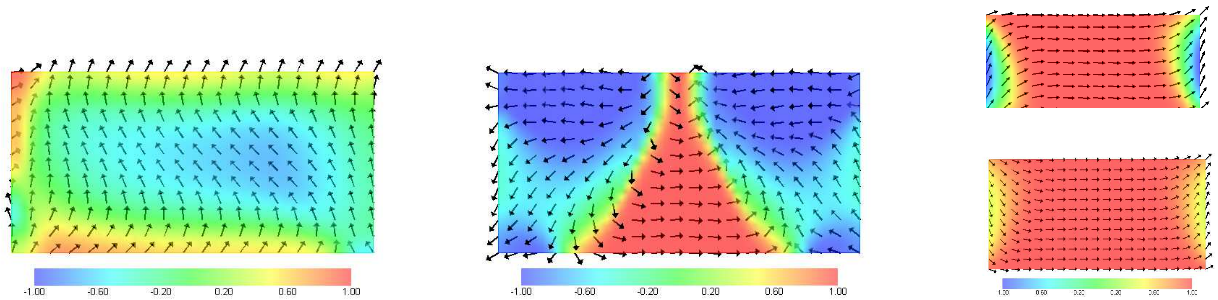


Figure 3. Numerical results. Plot of $<m_x>^2 + <m_y>^2 + <m_z>^2$ vs time in the interval ($0,t_0$) for damping (right) and precessional switching (left).

As far as the uniformity of magnetization is concerned, we consider the sum of the square values of the average magnetization components $<m_x>^2 + <m_y>^2 + <m_z>^2$ (< > means spatial average) as a measure of the uniformity of the switching process; the results are reported in figure 3-4. One can easily observe that precessional switching (figure 3-4a) is a quasi-uniform process, because the sum of the square values of the average magnetization components remain almost constant during time and close to unity, whereas for damping switching it decreases rapidly towards zero, showing the occurring of domain nucleation and domain wall motion (figure 4b). Thus we can conclude that for precessional switching, in our case of thin-film medium, one can reasonably apply the uniform mode theory to predict the duration of the external field pulse, which is necessary to achieve successful switching. To this end, let us now consider a uniformly magnetized ellipsoidal particle: in this case the magnetostatic field can be expressed analytically using the so-called demagnetizing factors N_x, N_y, N_z. The thin-film is modeled by an ellipsoidal particle with $N_x << N_z$, $N_y << N_z$. The magnetization dynamics is governed by Landau-Lifshitz-Gilbert equation:



(a) (b) (c)

Figure 4. Numerical results. (a) Precessional switching: magnetization vector field at $t=t_0$. (b) Damping switching: magnetization vector field at $t=t_0$. The applied field strength is $H_a = 19.51\,\mathrm{kA/m}$. (c) S-state (top), C-state (bottom).

$$\frac{d\mathbf{m}}{dt} = -\mathbf{m} \times \mathbf{h}_{\mathrm{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt}, \tag{3}$$

where time is measured in units of $(\gamma M_s)^{-1}$ and the (normalized) effective field $\mathbf{h}_{\mathrm{eff}} = \mathbf{H}_{\mathrm{eff}} / M_s$ has now the following expression, provided that the exchange field is zero:

$$h_{\mathrm{eff}} = -D_x m_x \mathbf{e}_x - D_y m_y \mathbf{e}_y - D_z m_z \mathbf{e}_z + h_a \mathbf{e}_y, \tag{4}$$

The coefficient $D_x < D_y < D_z$ take into account the demagnetizing effects and crystalline anisotropy, h_a is the normalized applied field and $\mathbf{e}_y$ the unit vector along the cartesian axis y. The relationship between the material parameters and the coefficients D_x, D_y, D_z are:

$$D_x = N_x - \frac{2K_1}{\mu_0 M_s^2} \quad , \quad D_y = N_y \quad , \quad D_z = N_z \quad . \tag{5}$$

We follow now the line of reasoning used in [5]: for short field pulses and small damping, it is possible to neglect the dissipative effect with respect to the magnetic torque. For this reason, we assume $\alpha = 0$ in (3). Eq. (3), in the conservative case, admits the two following integrals of motion:

$$m_x^2 + m_y^2 + m_z^2 = 1 \tag{6}$$

$$\frac{1}{2} D_x m_x^2 + \frac{1}{2} D_y m_y^2 + \frac{1}{2} D_z m_z^2 - h_a m_y = g_0 \tag{7}$$

representing respectively magnetization modulus conservation and energy conservation, being g_0 the initial energy. By considering the appropriate linear combination of equations (6) and (7), the following expressions can be obtained:

$$m_x^2 = \frac{2}{D_z - D_x}\left[\left(\frac{1}{2}D_x - g_0\right) - h_a m_y - \frac{1}{2}\left(D_x - D_y\right) m_y^2\right] = P_1(m_y) \tag{8}$$

$$m_z^2 = \frac{2}{D_z - D_x}\left[\left(g_0 - \frac{1}{2}D_x\right) + h_a m_y - \frac{1}{2}\left(D_y - D_x\right) m_y^2\right] = P_3(m_y) \tag{9}$$

The fact that m_x and m_z can be expressed as function of m_y, allows to write a differential equation for m_y only, which can be solved by separation of variables using the appropriate Jacobi elliptic functions. In particular, the period of the oscillation can be derived. To this end, we need the expression of the roots of the polynomials $P_1(m_y)$ and $P_3(m_y)$, which, in our case, are all real:

$$\mu_\pm = -\frac{h_a}{D_z - D_y} \pm \sqrt{\frac{h_a^2}{(D_z - D_y)^2} + \frac{D_z/2 - g_0}{D_z/2 - D_y/2}}, \tag{10}$$

$$\nu_\pm = -\frac{h_a}{D_y - D_x} \pm \sqrt{\frac{h_a^2}{(D_y - D_x)^2} + \frac{g_0 - D_x/2}{D_y/2 - D_x/2}} \tag{11}$$

It is shown in [5] that the period T of the oscillation is:

$$T = 8K(k)[(D_z - D_y)(D_y - D_x)(\nu_+ - \nu_-)(\mu_+ - \mu_-)]^{-1/2} \tag{12}$$

where $k^2 = [(\mu_+ - \nu_-)(\nu_+ - \mu_-)]/[(\nu_+ - \nu_-)(\mu_+ - \mu_-)]$ is the modulus of the elliptic function and $K(k)$ is the complete elliptic integral. Consequently, the switching time is defined as half period

$T_s = T/2$. It is also shown in [5] that a critical value of the external applied field exists and that below this value $h_{crit} = (D_y - D_x)/2$, the precessional switching of the particle does not occur; it is important to underline that h_{crit} is half the critical Stoner-Wohlfarth value $h_{SW} = D_y - D_x$.

We performed a set of micromagnetic numerical simulations of the precessional switching process for the values of H_a and T_s specified in table 1. This table reports the switching time T_s, analitically computed using eq. (12), for different values of H_a.

h_a / h_{SW}	1.0	1.1	1.2	1.3	1.4	1.5
H_a [kA/m]	13.01	14.31	15.61	16.91	18.21	19.51
T_s [ns]	0.194	0.181	0.171	0.162	0.155	0.149

Table 1. Analytically computed external field pulse duration T_s for different values of the external field strength H_a. These values are used in micromagnetic simulations of precessional switching.

The simulations were started from two different initial magnetization configurations which can be typically observed in the experiments on thin-film media: the so-called S-state and C-state (fig. 4(c)).

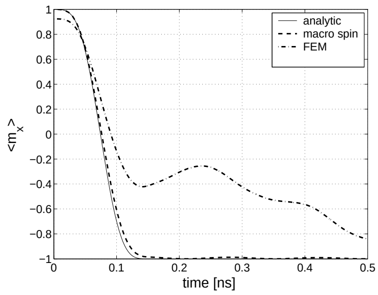
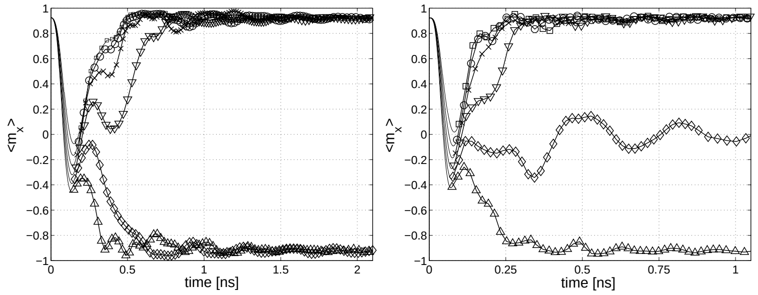


Figure 5. Analytical and numerical solutions of Landau-Lifshitz-Gilbert equation. Plot of $<m_x>$ vs time. $h_a = 1.5 \times h_{SW}$, $D_x = 1.2 \times 10^{-3}$, $D_y = 0.0175$, $D_z = 0.9763$.



(a) (b)

Figure 6. Numerically computed $<m_x>$ as a function of time. S-state (a), C-state (b) initial condition. (In both figures) symbol "□" for $h_a = h_{SW}$; "O" for $h_a = 1.1 \times h_{SW}$; "X" for $h_a = 1.2 \times h_{SW}$; "∇" for $h_a = 1.3 \times h_{SW}$; "◊" for $h_a = 1.4 \times h_{SW}$; "Δ" for $h_a = 1.5 \times h_{SW}$.

In figure 5 a comparison between the analytical solution of eq. (3) with $\alpha = 0$, the numerical solution of eq. (3) with $\alpha = 0.02$ for a uniformly magnetized thin-film shaped ellipsoidal particle (macrospin model) and the finite element solution of eq. (1) is reported for an applied field strength $h_a = 1.5 \times h_{SW}$. In the undamped case, at time $t = T_s$ the magnetization is exactly in the reversed position, so, switching off the external field, it remains definitely in this state; if the damping term is added in equation (3), one can see that after $t = T_s$ there is a small oscillation of $<m_x>$ because the system is not yet in the minimum energy state; in the general nonuniform case one can easily see that the uniform mode theory provide anyway a reasonably good information about the duration of the field pulse, but the presence of nonuniform modes produces an oscillation that can bring magnetization back to the initial state as one can see in figures 6(a)-(b). For this reason, a field strength $h_a = 1.5 \times h_{SW}$ is required to achieve successful switching starting from either an S-state or a C-state. We observe that this value is moderately larger than the critical value provided by uniform mode theory, $h_{crit} = h_{SW}/2$.

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