Switching Simulations in Perpendicular Media: Spin Wave Instabilities

P. B. Visscher, D. M. Apalkov, and Xuebing Feng

Abstract— **We have simulated the switching process in a perpendicular medium, using a simple model of a monopolar head, and visualized it by plotting the magnetizations of computational cells as a swarm of points on the time-varying contour plot of the Stoner-Wohlfarth energy. This viewpoint clarifies the spin wave instability that leads to switching. We find that the exchange interaction leads to energy flow and hence energy dispersion within a grain, leading to incoherence and switching.**

Keywords— **perpendicular recording, switching, spin waves**

I. Introduction

UNDERSTANDING and being able to simulate the mechanism of fast switching is very important for the development of perpendicular recording[1]. In addition to well-known mechanisms such as curling and domain-wall motion, there has been recent work[2] on a mechanism we will refer to as "spin-wave switching". We have previously studied spin wave switching for a very simple field pulse (a reverse field suddenly applied and left on)[3] and found that it can be understood in terms of an exponentially growing spin wave instability. A visualization technique in which the spin wave amplitudes are displayed in reciprocal space was used, and showed that the switching occurs because of an exponentially growing spin wave mode.

In the present paper, we study and visualize a similar spin wave switching mechanism in the context of perpendicular recording. In this case the field experienced by a grain of the recording medium increases slowly from zero as it approaches the head, goes through a maximum as it passes under the head, and then decreases slowly. In this scenario we avoid a problem that plagues simple field-reversal simulations, namely how to break the symmetry and get the magnetization to leave the easy axis. However, we find that a simple Stoner-Wohlfarth model still does not correctly predict the switching – thermal fluctuations in the initial state, amplified by a spin wave instability, are still necessary to get efficient switching.

The visualization plan adopted in this paper is to show the trajectories on a contour map of the Stoner-Wohlfarth energy. A slightly incoherent system can be represented by a swarm of points on such a contour plot. The rapid dispersion of this swarm signals the breakup of coherence that leads to switching.

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II. Head and medium model

We have chosen a very simple single-pole model with a soft underlayer, shown in Fig. 1, for the perpendicular-recording head. The field of a head such as that sketched is largest near the leading pole; near the center of the track it can be well approximated by the field of a line charge, proportional to $1/r$ where r is the distance from the center of the pole. We assume the soft underlayer has infinite permeability so there is a symmetrically-placed image pole, as shown. The geometry of this head is determined by the medium thickness 12 nm and the head-to-medium distance $h = 8$ nm. We assume a head velocity of $v = 20$ m/s. We compute the field at the center of the grain, and choose the head field so the maximum head field is 5.4 KOe $= 4.3 \times 10^5$A/m.

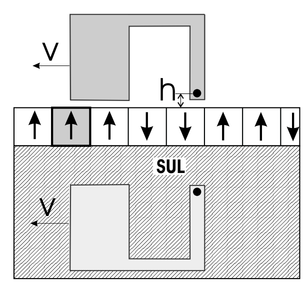

Fig. 1. Model for head and medium. We include only the field from the leading pole (solid circle) and its image in the SUL (soft underlayer), modeled as line charges perpendicular to the plane of the figure. The vector labeled "v" is the velocity of the head (and its image) with respect to the medium.

III. Micromagnetic calculation

The micromagnetic calculation is based on the standard Landau-Lifshitz (LL) equation for the time evolution of the magnetization $\mathbf{M}$ of a computational cell[4]

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} - \frac{\alpha\gamma}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}) \quad (1)$$

The constant $\gamma = 17.6$ (KOe ns)$^{-1} = 2.2 \times 10^5$ (A/m s)$^{-1}$ is the gyromagnetic ratio, and α is the LL damping coefficient. The total magnetic field $\mathbf{H}$ consists of an external field, an exchange field, an anisotropy field, the magnetostatic fields of other cells, and a random thermal field. The thermal fields are extremely important in that they create the spin wave fluctuations that grow exponentially to cause switching. However, in the present simulations these fluctuations are created slowly over a long period of time before our simulation begins, i.e. they are included in the initial condition. Thus we use an initial condition chosen from a canonical ensemble at a temperature of 300 K, and we can omit the random thermal fields and the damping coefficient α during the simulation itself; their effect during fast switching is negligible. We are not attempting to model the dissipation of energy after the breakup of coherence (note that the normalized magnetization never goes to -1 in Fig. 2), for which the damping is of course critical – without it, the system can't get rid of the spin wave energy. For these initial studies we have also omitted the magnetostatic fields - though the vertical demagnetization can be quite large, the uniform part of the field is accounted for by an effective anisotropy field H_K. Torques due to lateral variations in magnetization, though smaller, may be significant, and will be investigated in a later paper.

Thus our total field is

$$\mathbf{H}(\mathbf{r}) = \mathbf{H}^{\mathbf{ext}} + \sum_{\delta} J\mathbf{M}(\mathbf{r}+\delta) + \frac{H_K}{M_s}(\mathbf{M}(\mathbf{r})\cdot\widehat{\mathbf{e}})\widehat{\mathbf{e}}. \quad (2)$$

Here $\mathbf{H}^{\mathbf{ext}}$ is the external (head) field, J is the exchange integral, each cell is labeled by its center $\mathbf{r}$, $\mathbf{r}+\delta$ is one of the six nearest neighbors, $\widehat{\mathbf{e}}$ is a unit vector along the easy axis (taken to be the z axis in this paper, perpendicular to the plane of the thin film medium), and H_K is the anisotropy field. We have used anisotropy field $H_K = 6$ KOe $= 4.78\times10^5$A/m, exchange constant $A = \mu_0 J M_s^2 a^2$ $= 1.3\times10^{-11}$J/m^3, and the dimensionless exchange parameter (Eq. 2) $J = 0.05$. We have used a quaternion algorithm[5] which facilitates 3D visualization[3], and periodic boundary conditions in the film plane.

IV. Switching results

We have used two discretizations of a switching grain: 64 cells ($4\times4\times4$) and $1\times1\times1$, the latter being a coherent Stoner-Wohlfarth system that we use to plot the contours of the Stoner-Wohlfarth energy[6]

$$E = -\mathbf{M}\cdot\mathbf{H}^{\mathbf{ext}} - \frac{H_K}{2M_s}(\mathbf{M}\cdot\widehat{\mathbf{e}})^{\mathbf{2}}. \quad (3)$$

The evolution of the perpendicular component of the magnetization as the grain passes the head is shown in Fig. 2, with and without fluctuations and exchange. The basic conclusion is that exchange is necessary in order to achieve switching; in the rest of the figures we will show why that is the case.

When our grain is far from the head, the magnetization points along the total field (mostly anisotropy field, in the z direction perpendicular to the film) except for the small thermal fluctuations discussed above. In the contour plot [Fig. 3(a)], the point representing the magnetization rests at an energy minimum. The minimum gradually moves to the left [away from the origin in Fig. 3(b), in the direction of the head field] as the head field increases. As long as the field changes slowly, $\mathbf{M}$ remains at this minimum. (This would only be obvious if we included damping; it turns out that it follows the minimum quite closely even without damping.)

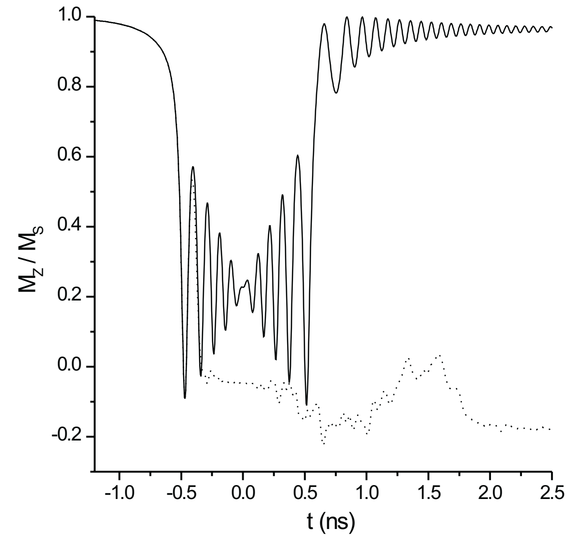

Fig. 2. The variation of the perpendicular component of $\mathbf{M}$ with time, for the $1\times1\times1$ (Stoner-Wohlfarth) system (solid line), and the $4\times4\times4$ system with exchange (dotted line). At $t = 0$, the grain is directly below the head.

But as the grain approaches the head, the field changes more rapidly, and the magnetization begins to precess around the minimum. At the same time, the minimum is getting shallower (as the reversing field, the perpendicular component of the head field, cancels more of the anisotropy field) and at time $t = -0.63$ ns (between Fig. 3 and Fig. 4) it disappears – this is the Stoner-Wohlfarth instability.

The magnetization then finds itself on the side of a high maximum, and follows a precessional orbit around this maximum, which in this case dips down below the equator of the unit sphere [a circle of radius 1.57 in Fig. 4(a)]. The overall effect is that $\mathbf{M}$ changes rather slowly until the local minimum disappears, then rather suddenly starts precessing rapidly in a large orbit. In an incoherent system this rapid motion has the effect of spreading the "+" symbols (each representing the $\mathbf{M}$ of one computational cell) out along the orbit: the small initial variation in energy (of order k_BT) produces a variation in orbital speed and a "straggling" effect. This spreading is not yet visible in Figs. 3 and 4, but in Fig. 5(a) the "+" symbols spread into a streak along the orbit, in the absence of exchange interaction ($J = 0$).

Fig. 5(b) shows the result of turning on exchange ($J = 0.05$). The straggling effect tilts the $\mathbf{M}$s relative to their neighbors, around which they then precess. This moves some cells up or down in energy (along the energy gradient, perpendicular to the energy contours), creating a much larger spread in energy, hence further straggling; mathematically this translates into an exponentially growing instability, which very quickly spreads the "+" symbols throughout the contour plot, completely destroying the coherence. This corresponds to the separation of the incoherent from the coherent-system lines in the M *vs* t plot (Fig. 2), and indicates irreversible switching. After this, the coherent-system contour plot is no longer relevant for

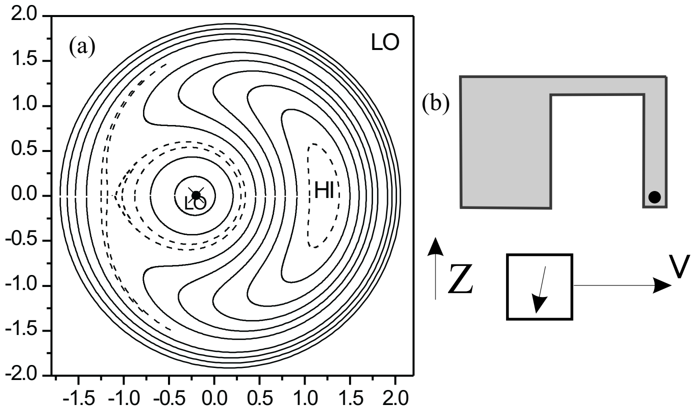

Fig. 3. The system at time $t = -1.0$ ns. (a) Contour plot of Stoner-Wohlfarth energy with the Stoner-Wohlfarth ($1 \times 1 \times 1$ cell system) magnetization shown as a large $\times$ and the 64 magnetizations of the $4 \times 4 \times 4$ cell system shown as small + signs (which merge into one another at this early time.) This is a polar plot, looking down on the unit sphere from the $+z$ direction; the radial coordinate is the colatitude θ and the azimuthal coordinate is ϕ, where θ and ϕ have their usual spherical-coordinates meanings. This projection is highly distorted near the south pole ($-z$ direction), which would be a circle of radius π. However, we don't need to visualize this region, only to realize that there is an absolute minimum of energy there, indicated by "LO" in the corner of the figure. There is a local minimum near the north pole, also labeled "LO"; the absolute maximum labeled "HI" is on the equator when the external field is small, but has moved north a bit by this time. Solid-line contours are equally spaced in energy; some extra dashed contours are drawn to give more detail near the maximum and the saddle point. (b) Relative positions of grain and head, showing the head field and the velocity vector of the medium.

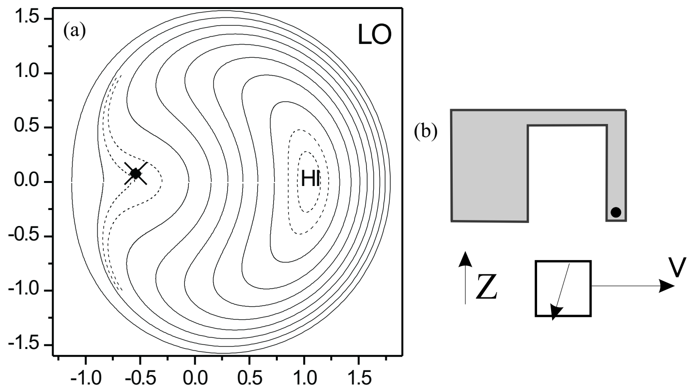

Fig. 4. The system at a later time $t = -0.60$ ns. (a) Energy contour plot. The local minimum and the saddle point have annihilated each other, and **M** is now precessing in a large orbit. (b) Grain and head.

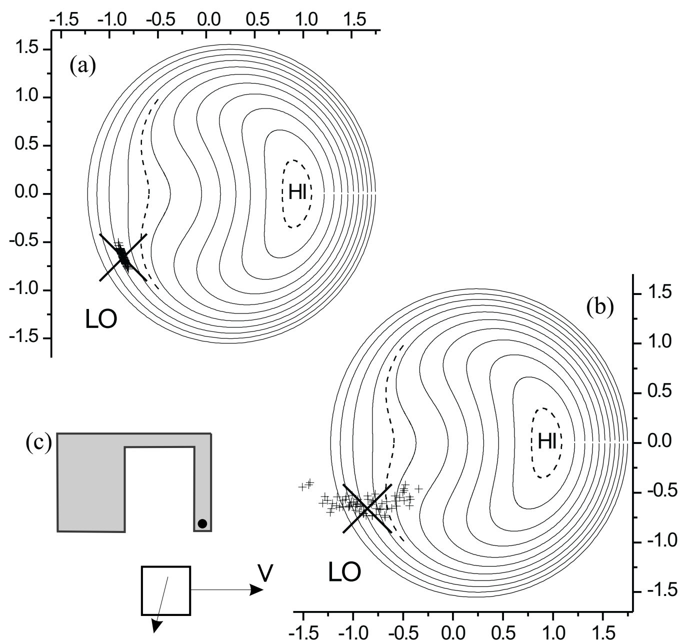

Fig. 5. The system at time $t = -0.43$ ns. (a) Energy contour plot with **M**s without exchange, (b) with exchange. Now the +'s representing individual cells can be distinguished. (c) Grain and head.

the exchange-interacting system – we show only the system without exchange in the last figure (Fig. 6). Here we can see the origin of the upward "unswitching" jump in $M_z(t)$ in Fig. 2; when the relative minimum reappears (Fig. 6) it can trap the precessing streak of points, because without exchange, it is still not very dispersed in energy.

V. Conclusions

We have presented visualizations of the mechanism of switching of perpendicular media, which clarify the role of the exchange interaction in spin wave switching. In future work we plan to visualize the spatial variation of the magnetization during the spin wave instability.

VI. Acknowledgements

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References

[1] R. Wood, Y. Sonobe, Z. Jin, and B. Wilson, *J. Mag. Mag. Mat.* 235 (2001).
[2] V. L. Safonov and H. N. Bertram, *J. Appl. Phys.* **85**, 5072.
[3] P. B. Visscher, O. Traistaru, D. M. Apalkov, and Xuebing Feng, "Visualization of spin waves during switching simulation", *J. Appl. Phys.* submitted for publication in **91**, (May 2002).
[4] J. Fidler and T. Schrefl, *J. Phys. D* **33**, R153 (2000).
[5] Xuebing Feng and P. B. Visscher, "Quaternion-based algorithm for micromagnetics", *Physical Review B* **65**, 104412, 2001.(http://bama.ua.edu/~visscher/mumag/quat.pdf)
[6] A. Aharoni, *Introduction to the theory of ferromagnetism*, Oxford U. P., 1996.

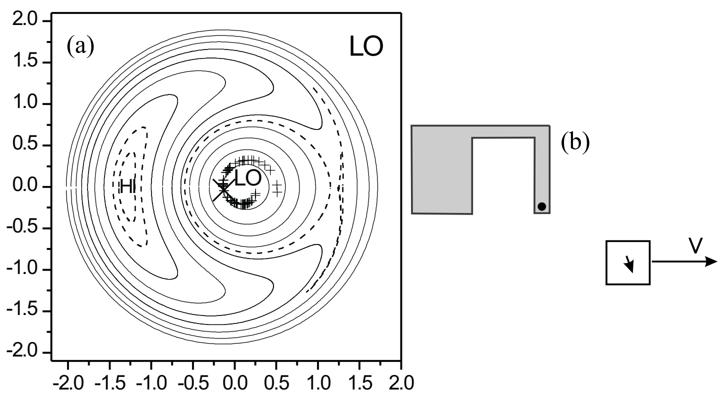

Fig. 6. The system at time $t = 1.26$ ns. (a) Energy contour plot. (b) Grain and head.