Switching Simulations in Perpendicular Media: Spin Wave Instabilities

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Outline

- We show the importance of exchange interactions (spin waves) in switching of perpendicular media. A simple model
  - doesn’t switch without exchange interaction (even if we allow incoherent thermal fluctuations)
  - does switch if we include exchange
- We visualize the trajectories of magnetization vectors on a contour map of the Stoner-Wohlfarth energy
- Switching takes place through a rather sudden spin wave instability
Head and Medium Model

- only the field from the trailing pole and its image in the SUL (soft underlayer) is included;
- the field is approximated by the field of a line charge, proportional to $1/r$, where $r$ is the distance from the center of the pole;
- $h = 8 \text{ nm}, \ v = 20 \text{ m/s}, \ s = 12 \text{ nm}$. 
Micromagnetic Calculation

Landau-Lifshitz (LL) equation:

\[
\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} - \frac{\alpha \gamma}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H})
\]

\(\gamma = 17.6 \text{ (KOe ns)}^{-1}\) is the gyromagnetic ratio;
\(\alpha\) is the LL damping coefficient (it is taken to be zero unless otherwise stated);
\(\mathbf{H}\) is the total magnetic field;
\(M_s\) is the saturation magnetization of the medium;

The initial condition was chosen from a canonical ensemble at a temperature of 300 K. (The resulting initial fluctuations are very important – they are the only source of incoherence in the model.)
Magnetic Field

\[ H(r) = H^{\text{ext}} + \sum_\delta J M(r + \delta) + \frac{H_K}{M_S} (M(r) \cdot \hat{e}) \hat{e} \]

- \( H^{\text{ext}} \) is the external (head) field, at \( t = 0 \) when the grain is right below the head;
- \( J = 0.05 \) is the exchange integral (dimensionless), corresponding to exchange constant \( A = \mu_0 J M_S^2 a^2 = 1.3 \times 10^{-11} \text{ J/m}^3 \);
- \( r \) is the center of each cell; \( r + \delta \) is one of the six nearest neighbours;
- \( \hat{e} \) is a unit vector along the crystallographic easy axis (taken to be the z axis, perpendicular to the plane of the thin film medium);
- \( H_K = 6 \text{ KOe} \) is the effective anisotropy field.

Excluded:

magnetostatic interaction (not so critical as exchange and anisotropy fields)
Time-dependence of $M_z$

At $t = 0$ the grain is directly below the head.

$t = -1.0$
$t = -0.6$
$t = -0.43$
$t = -0.35$
$t = 0.44$
$t = 0.76$

no exchange (nearly coherent), no damping

exchange is necessary to achieve switching

with exchange (incoherent; spin wave instability at $t \sim -0.4$ ns), no damping

damping is included ($\alpha = 0.07$)

4 x 4 x 4 system

At $t = 0$ the grain is directly below the head.
Evolution of Stoner-Wohlfarth Surface

With no external field, there are energy minima at the easy axes: the +z pole ("north pole", $\theta = 0$, the center of a polar plot) and –z pole. When we add a head field, its horizontal component moves both minima to the left, and creates a saddle point between them, as is shown in this polar plot of the Stoner-Wohlfarth energy contours:

The radial coordinate is the colatitude $\theta$, as in the usual spherical coordinates, and the azimuthal coordinate is $\phi$. Solid contours are equally spaced in energy; dashed contours are “extra” to show detail in flat regions.

The magnetization initially follows the energy minimum.

Relative positions of grain and head, showing the total field and the velocity vector of the medium.
The growing vertical component of the head field makes this minimum (near +z axis) shallower and the –z minimum deeper. The +z minimum and the saddle point approach each other and annihilate at \( t = -0.63 \) ns, leaving only one maximum and one minimum (the –z minimum). The magnetization follows the minimum as long as it exists. After it disappears the magnetization must follow a large orbit around the maximum ("HI").
The rapid motion in this orbit has the effect of spreading the \( \mathbf{M} \)'s out along the orbit: the small initial variation in energy (of order \( k_B T \)) produces a variation in orbital speed and a “straggling” effect:

\[
t = -0.43 \text{ ns}
\]

Now the +’s representing individual cells can be distinguished. The straggling effect tilts the \( \mathbf{M} \)'s relative to their neighbors, around which they then precess.

With exchange, we see an exponentially growing instability.

Grain and head.
**t = -0.37 ns**

This is a snapshot at $t = -0.37$ ns, except for the red line, which represents the coherent-system trajectory from $t = -0.40$ ns to $-0.34$ ns. At later times $> -0.34$ ns, the \( \mathbf{M} \)'s (+ signs) are scattered all over the sphere – the system has irreversibly switched (though \( \mathbf{M} \) will not relax to the -z axis unless we include some damping.)
\[ t = +0.44 \text{ ns} \]

From now on we show only the system without exchange interaction, which continues to precess rapidly, as indicated by the rapid oscillations in the M(t) graph.
$t = + 0.76 \text{ ns}$

We are far enough from the head that the anisotropy minimum near +z axis has reappeared, and the system has been trapped in the minimum. This is the “unswitching” event seen in $M(t)$. 

![Graph showing $M_z/M_S$ vs $t$]
Conclusions

• In our model of a perpendicular medium, switching takes place through a spin-wave instability (the system without exchange or without initial thermal fluctuations interaction does not switch)

• The dynamics can be visualized on a contour map of the Stoner-Wohlfarth energy.

Future work

• Including magnetostatic interaction (fast multipole method)