Micromagnetic Modeling

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Overview of modeling at MINT

• Electronic structure and transport (Butler)
• Mean field modeling (Harrell)
• Monte-Carlo modeling (non-LL) (Harrell)
• Landau-Lifshitz micromagnetic modeling (Visscher)
  • Dynamics, metastability in thin permalloy films (Feng)
  • Current-driven switching (Apalkov)
  • Nanosecond switching of perpendicular media (Misra)
  • Switching of FePt nanoparticle arrays (Feng)
  • Simplified FMM code (Apalkov)
Micromagnetic modeling: Landau-Lifshitz equation

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

\( \alpha \) = dimensionless Landau-Lifshitz damping coefficient.

\( \mathbf{H} = \mathbf{H}_{\text{external}} + \mathbf{H}_{\text{exchange}} + \mathbf{H}_{\text{anisotropy}} + \mathbf{H}_{\text{demag}} + \mathbf{H}_{\text{random}} \)

Where \( \mathbf{H}_{\text{exchange}} = \sum J \mathbf{M}_{\text{nbr}}, \ J = \text{exchange integral}, \)

\( \mathbf{H}_{\text{demag}} = \text{sum over all other cells; time consumed } \sim N^2 \)

Order-N alternative: fast multipole method (FMM).

- Applied to magnetic systems [Visscher & Gunal, J.App. Phys. 81, 3827 (1996)]

Recent FMM innovations (w/ D. M. Apalkov)

- Cartesian harmonic formulation
- recursive calculation of kernels using self-similarity (POSTER)
- recursive calculation of infinite sums over periodic images
- charge-based FMM

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Basic idea of FMM

Rationale -- MRAM example:

Subdivide rectangular elements into grid (N~10^5 cells)

O(N^2) interactions

H~M/r^3+Quad/r^4...

FMM lumps cells together hierarchically
Hard-axis pulse experiment


- Initially $M$ along easy axis
- Apply hard axis field pulse.
- $M$ swings toward this field.

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Mathematical Isomorphism with Particle on Circular Track—“Roller Coaster”

Rewrite Landau-Lifshitz equation:
\[
\frac{dM}{dt} = -\gamma M \times H
\]

In terms of \(\phi\) and \(M_z\):
\[
\frac{d\phi}{dt} = -\gamma M_z, \quad \frac{dM_z}{dt} = \gamma M_s \frac{\partial E}{\partial \phi}
\]

+ terms of order \(H_{\text{applied}}/M_s \leq 10^{-3}\)

Particle motion on circle:
\[
\frac{d\phi}{dt} = v, \quad m \frac{dv}{dt} = -\frac{\partial E}{\partial \phi}
\]

- \(\gamma M_z\) is analog of velocity \(v\)

LLG damping in film \(\rightarrow\) viscous damping in roller coaster

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Experiment vs uniform simulation


Single-domain LLG simulation result

“metastability”
Non-uniform simulation (+roller-coaster visualization)

(visualization by Xiaoguang Deng & Xuebing Feng, at http://bama.ua.edu/~visscher/mumag/roller.html)

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Results of permalloy simulation

• Roller Coaster analogy of thin film dynamics helps intuition.
• “Metastability”

Future work

• Including magnetostatic interaction (blocks rotation in incoherent case)
• Simulate larger system (ripple domains)
Current-driven switching

We are working on modeling current-driven switching experiments similar to that of the Cornell group [F. J. Albert *et al*, APL 77, 3809 (2000)].

Current is passed upward through a thick (40 nm) layer of Co, a thin (3 nm) Cu spacer into a thin (3 nm) layer of Co, which switches. Temperature = 24K. Initial state:
Plan view of thin layer: movie

Using simplest model of current-driven torque: in thin layer, 
\[ \frac{dM}{dt} \text{ has term } \propto M \times M \times M_{\text{thick}} \] (for now)

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Plans for current-driven switching simulation

- Incorporate first-principles torque term
  Slonczewski model, reflection and transmission calculated from correct electron wavefunctions (Butler, Velev)
- Study reversal modes
Simulation of nanoparticle arrays

• Synthesized by Nikles and Harrell groups

• Simulation approaches:

  ° Mean field -- approximate but analytic

  ° Monte Carlo -- no collective reversal, but fast

  ° Landau-Lifshitz micromagnetics -- allows collective reversal, but slow (so far)

Try LL micromagnetics for hysteresis loop of hexagonal array of spherical 4 nm FePt particles.
Movie of hysteresis loop

hexagonal array of 4 nm FePt particles:

- 4 x 8 periodic array
- Full FMM magnetostatic interactions (infinite # images)

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Hysteresis loop with magnetostatic interactions

\[ \frac{dH}{dt} = 10 \text{KOe/ns} \]

\[ \frac{dH}{dt} = 5 \text{KOe/ns} \]

\[ 4\pi M_x \text{ (KOe)} \]

\[ H \text{ (KOe)} \]

No interactions
Movie: $H = 0$ to $-1.7 \text{kOe}$

$4\pi M = 7$ to $-0.5 \text{kOe}$
Future work on nanoparticle arrays

• Study reversal mechanisms
• Longer times
• Binary (keepered) arrays of FM and SPM particles -- collective reversal critical, need full micromagnetics
Switching of perpendicular media

Parameters: $M_s = 8.02$ kOe
$A = 5 \times 10^{-12}$ A/m
$H_K = 9.0$ kOe

Future: simulate longer times:
Summary of micromagnetic modeling work

- Simplified FMM code for demag field
- Magnetization dynamics in thin permalloy films
- Current-driven switching simulation
- Nanosecond switching of perpendicular media
- Switching of FePt nanoparticle arrays