Micromagnetic Simulation of Magnetic Systems

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Introduction: Magnetism is everywhere. It's easy to simulate the electromagnetic fields in materials using AC/DC module. However, method based on Maxwell's equations is not sufficient for ferromagnetic materials with spontaneous magnetization, especially for the mesoscopic spin (magnetic moment) dynamics.

Method: The spin dynamics of ferromagnetic systems can be described by the Landau-Lifshitz-Gilbert (LLG) equation, where the effective field includes exchange interaction, anisotropy, Dzyaloshinskii-Moriya interaction (DMI), inter-layer coupling etc. In this formalism, the local magnetization is treated as a macro-spin with conserved magnitute (a unit vector on a Bloch sphere). The LLG equation is implemented via Weak Form in mathematic module.

$$\dot{\mathbf{m}}(\mathbf{r},t) = -\gamma\mathbf{m}(\mathbf{r},t)\times\mathbf{H}_{\text{eff}} + \alpha\mathbf{m}(\mathbf{r},t)\times\dot{\mathbf{m}}(\mathbf{r},t)$$

Effective field $$\mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0 M_s}\frac{\delta E}{\delta\mathbf{m}}$$

Conserved magnitute $$\begin{cases}\mathbf{M}(\mathbf{r},t) = M_s\mathbf{m}(\mathbf{r},t)\\ |\mathbf{m}(\mathbf{r},t)| = 1\end{cases}$$

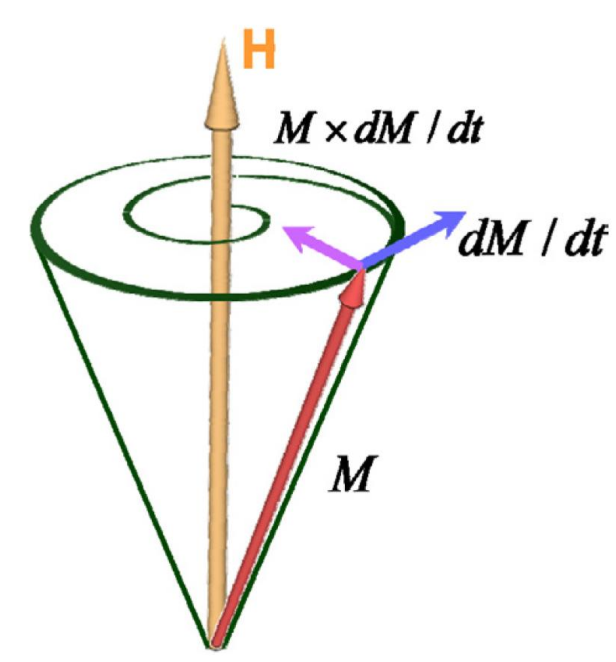
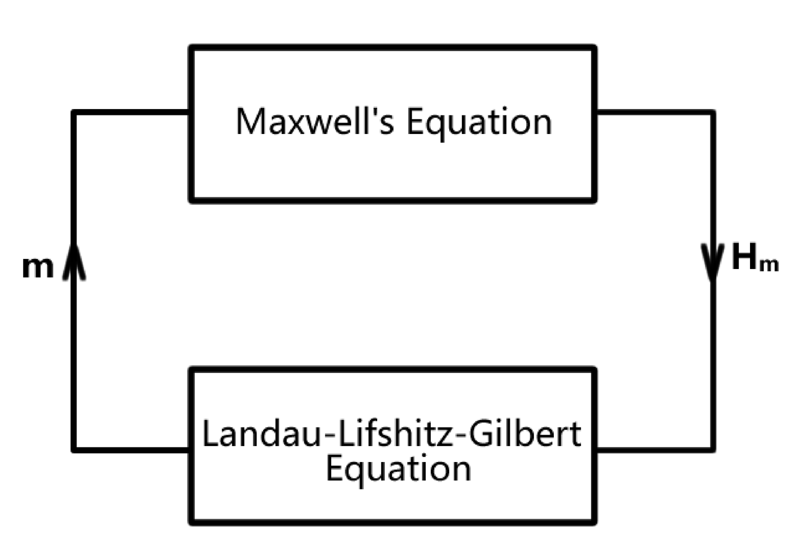


Fig 1. Spin Precession [2]

In order to include long-range dipolar interaction, we can either input the analytical dipolar field into the LLG equation or utilize the powerful multiphysics coupling of COMSOL by solving LLG equation and Maxwell's equation (AC/DC module) simultaneously.

$$\mathbf{H}_m = \frac{M_s}{4\pi}\int\left[\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right]d\mathbf{r}$$

or $$\nabla\cdot\mathbf{H}_m = -\nabla\cdot\mathbf{M}$$



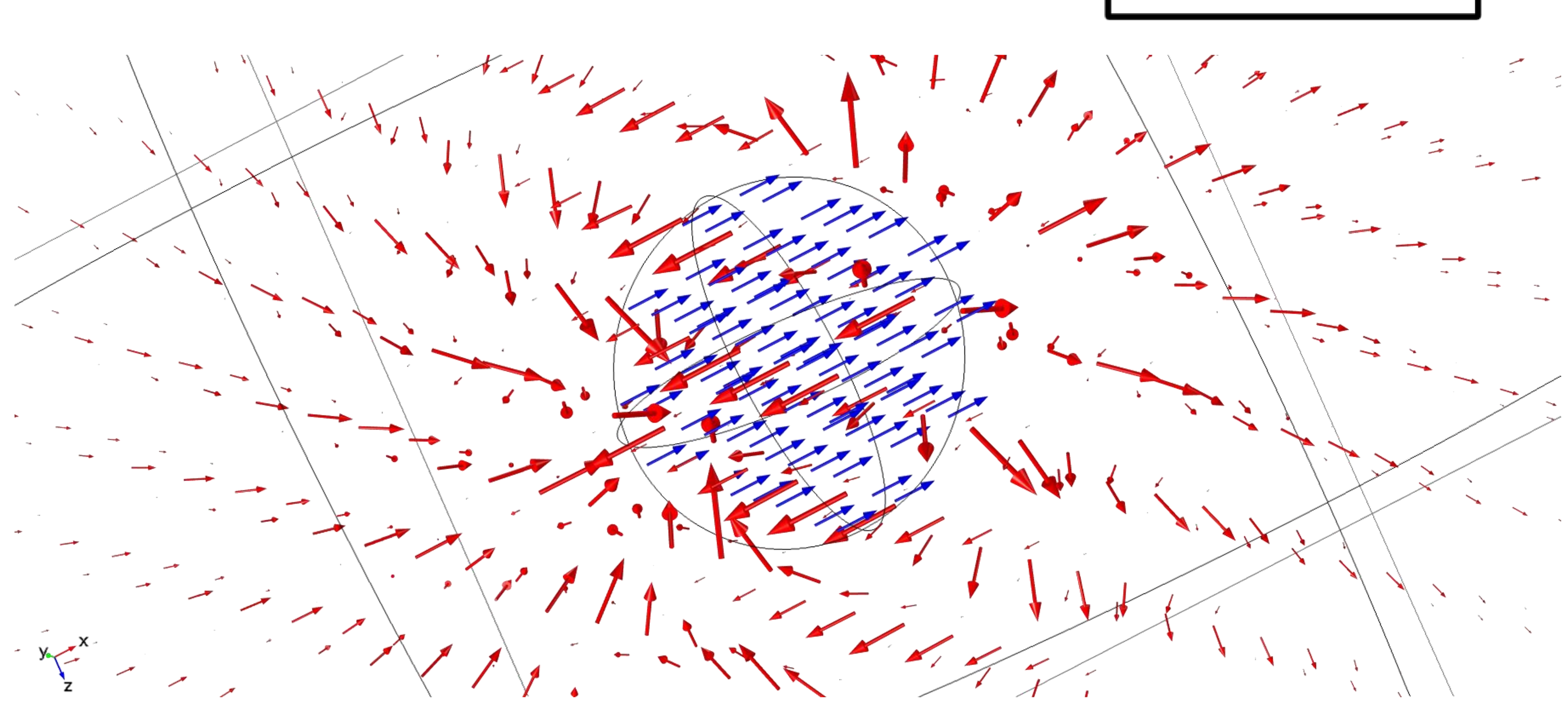


Fig 2. By solving LLG equation and Maxwell's equation simultaneously, we can get a full description of dynamical magnetic systems.

Spin waves: Spin waves are collective excitations of magnetization. The precession of local spin can propagate spatially and temporally due to the short-range exchange interaction or long-range dipolar interaction. Spin waves are promising candidates for next-generation information technology.

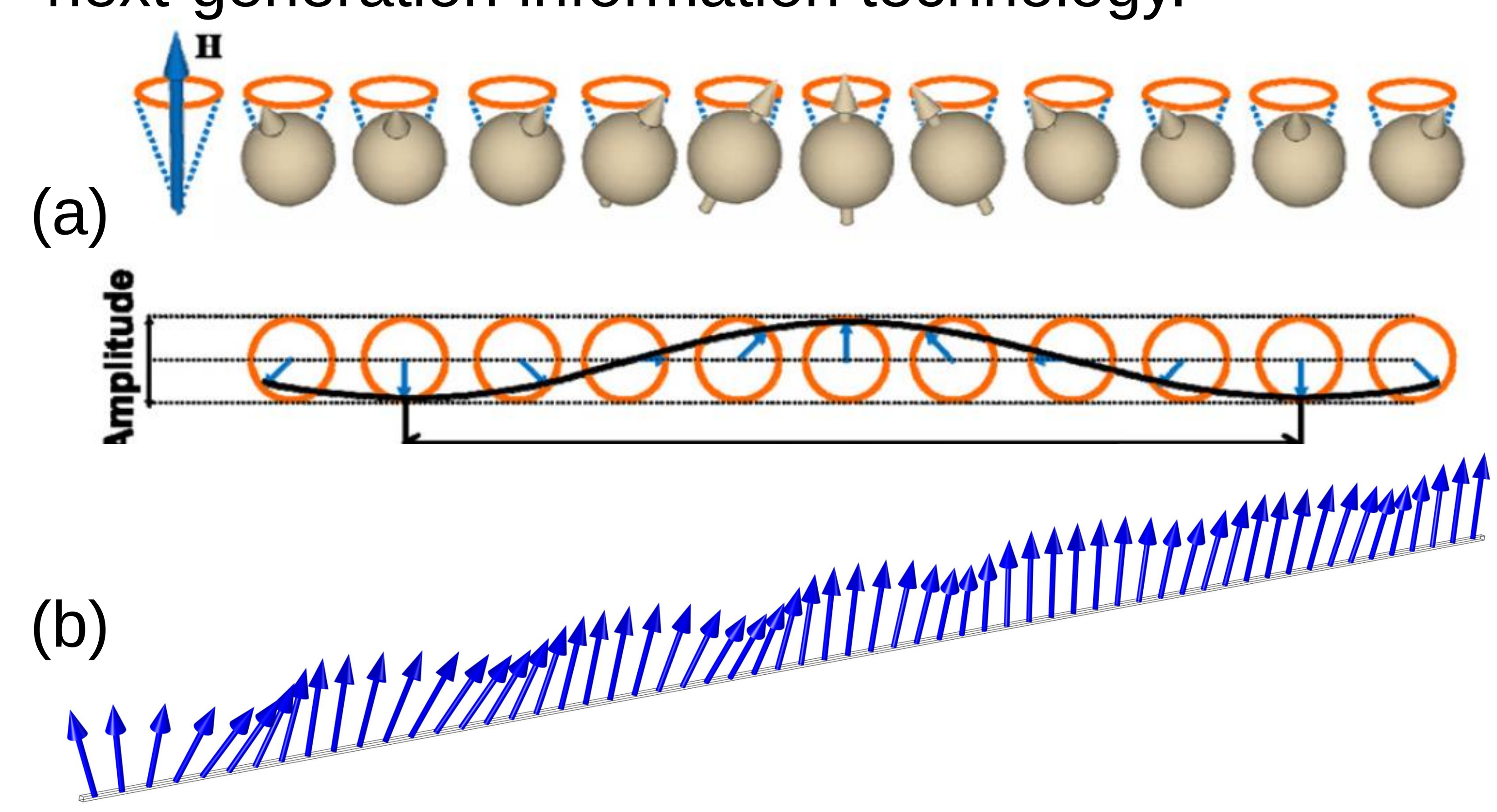
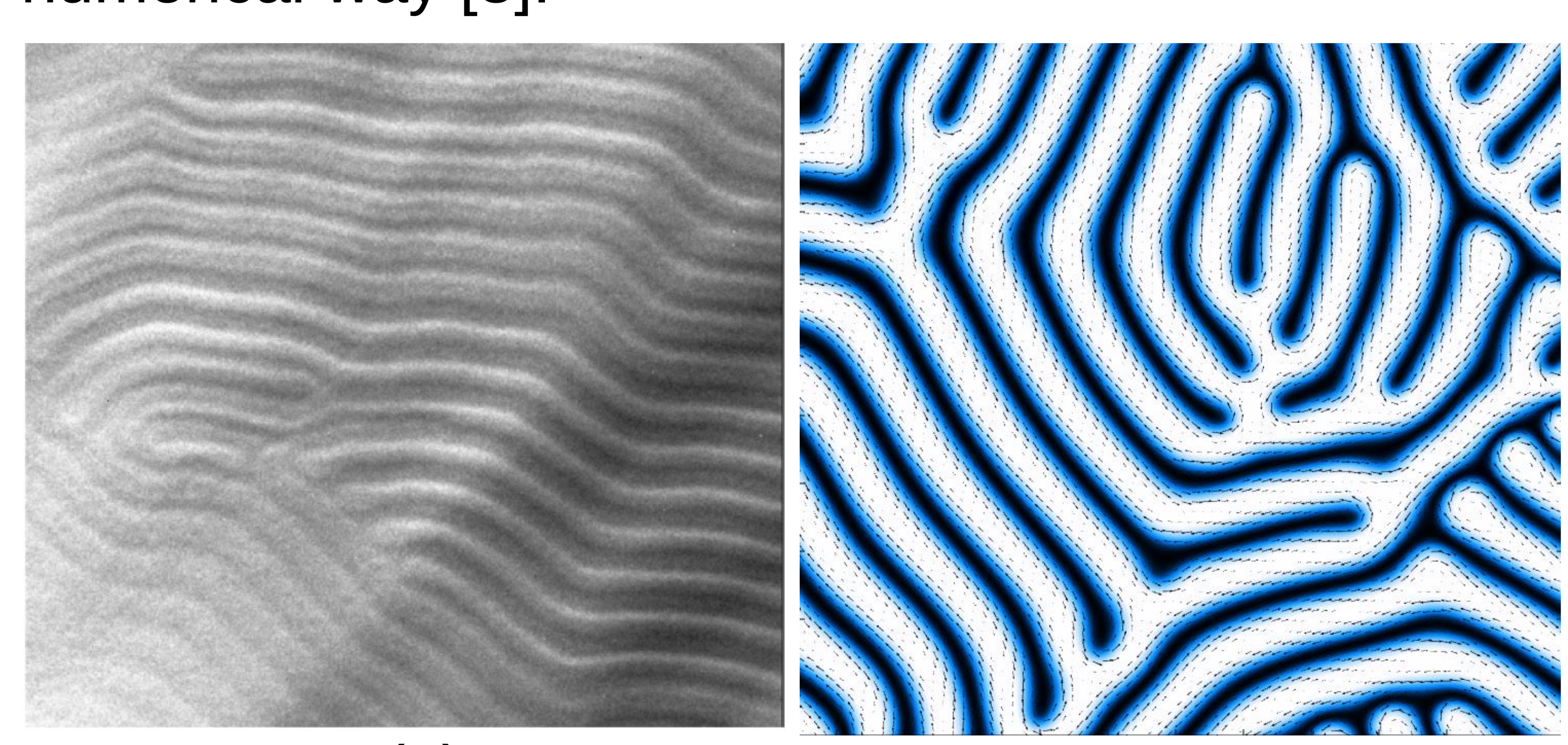


Fig 3. (a) Schematic of spin waves [2]. (b) Simulation of spin waves by COMSOL. Each blue arrow represents local magnetization.

Magnetic texture: Due to the competition of various interaction, magnetic domains are formed to reduce energy. The dynamics of magnetic texture such as domain wall, vortex, spiral and skyrmion can be simulated. Furthermore, the interaction between spin waves and magnetic texture can be studied in a numerical way [3].



(a) (b)

Fig 4. (a) Magnetic stripe domains observed in experiment by TEM [4]. (b) Simulation of magnetic stripe domains by COMSOL where colors represents out-of-plane magnetization.

Future work :

(1) Spin wave devices: spin wave circuit, spin wave diode, spin wave fiber etc [5-7].

(2) Multiphysics coupling: magneto-elastic coupling, magneto-optic coupling, thermal effect etc.

Reference：

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