Nanofabricação

Aula 5 – Prof. Gomes

18 jul 2008

"let's dance the last dance"

Introdução às Simulações Micromagnéticas

Ferramenta importante para o estudo teórico e previsão do comportamento magnético de estruturas, em particular de nanoestruturas magnéticas.

Landau–Lifshitz equation

The dynamics of the magnetization distribution in a ferromagnetic material is described by the Landau–Lifshitz equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma(\mathbf{M} \times \mathscr{H}) - \frac{\alpha\gamma}{M_s}\mathbf{M} \times (\mathbf{M} \times \mathscr{H}),$$

with the boundary condition

$$\frac{\partial \mathbf{M}}{\partial \nu} = 0,$$

where the vector m represents the unit outward normal on the boundary of the ferromagnetic sample. $|\mathbf{M}| = M_s$ is the saturation magnetization, and is usually set to be a constant far from the Curie temperature;

γ is the gyromagnetic ratio. The first term on the right-hand side is the gyromagnetic term and the second term is the damping term. α is the dimensionless damping coefficient.

$\mathscr{H}$ is the local field, computed from the Landau–Lifshitz free energy functional:

$$F(\mathbf{M}) = \frac{1}{2}\int_V \left\{ \frac{A}{M_s^2}|\nabla \mathbf{M}|^2 + \Phi\left(\frac{\mathbf{M}}{M_s}\right) - 2\mu_0 \mathbf{H}_e \cdot \mathbf{M} + \mu_0 \mathbf{M}\cdot \nabla U \right\} dx, \quad (3)$$

$$\mathscr{H} = -\frac{\delta F}{\delta \mathbf{M}} = \frac{A}{M_s^2}\Delta \mathbf{M} - \frac{1}{M_s}\Phi'\left(\frac{\mathbf{M}}{M_s}\right) + \mu_0 \mathbf{H}_e - \mu_0 \nabla U.$$

A is the exchange constant, $A|\nabla \mathbf{M}|^2/M_s^2$ is the exchange interaction energy between the spins, $\Phi(\mathbf{M}/M_s)$ is the energy due to material anisotropy, μ_0 is the permeability of vacuum, $-2\mu_0 \mathbf{H}\cdot\mathbf{M}$ is the energy due to the external field, V is the volume occupied by the material, and finally the last term in (3) is the energy due to the field induced by the magnetization distribution inside the material.

for constant external field and temperature, the equilibria (i.e. metastable states) are given by the minima of the free energy . Remembering that $\mathbf{M} = M_s\mathbf{m}$, the unknown will be the magnetization unit-vector field $\mathbf{m}$.

Landau–Lifshitz–Gilbert equation

An in principle different approach was proposed by Gilbert in 1955, who observed that since the conservative equation can be derived from a Lagrangian formulation where the role of the generalized coordinates is played by the components of magnetization vector M_x, M_y, M_z. In this framework, the most natural way to introduce phenomenological dissipation occurs by introducing a kind of 'viscous' force, whose components are proportional to the time derivatives of the generalized coordinates. More specifically, he introduces the following additional torque term:

$$\frac{\alpha}{M_s}\mathrm{M} \times \frac{\partial \mathrm{M}}{\partial t} \quad ,$$

which correspond to the torque produced by a field $-\frac{\alpha}{\gamma M_s}\frac{\partial \mathbf{M}}{\partial t}$, where $\alpha > 0$ is the Gilbert damping constant, depending on the material (typical values are in the range $\alpha = 0.001 \div 0.1$). We observe that, similarly to the case of Landau-Lifshitz equation, the additional term introduced by Gilbert preserves the magnetization magnitude . In the following section, when we will analyze the fundamental properties of magnetization dynamics, we will show that the Gilbert damping is connected to the assumption of a suitable Rayleigh dissipation function. Therefore, the precessional equation modified according to Gilbert's work, is generally referred to as *Landau-Lifshitz-Gilbert equation*:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \quad .$$

Eqs. L-L and L-L-G express different physics and are identical only in the limit of vanishing damping. Moreover, first Kikuchi and then Mallinson have pointed out that in the limit of infinite damping ($\lambda \to \infty$ in Eq. L-L , $\alpha \to \infty$ in Eq. L-L-G , the Landau-Lifshitz equation and the Landau-Lifshitz-Gilbert equation give respectively:

$$\frac{\partial M}{\partial t} \to \infty \quad , \quad \frac{\partial M}{\partial t} \to 0 \quad . \tag{1.89}$$

Since the second result is in agreement with the fact that a very large damping should produce a very slow motion while the first is not, one may conclude that the Landau-Lifshitz-Gilbert equation is more appropriate to describe magnetization dynamics.

The minimization of free energy is achieved by computational methods. Systems like OOMMF (Object Oriented MicroMagnetic Framework), are avaiable for free solving micromagnetic problems.

Estudo de Casos

- Transition from single-domain to vortex state
- Micromagnetic behaviour of electrodeposited cylinder arrays

gomes@cbpf.br