

TUTORIAL ON THE MICROMAGNETIC MODELING

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Micromagnetic simulations have recommended themselves as a useful tool to predict the hysteresis properties of magnetic materials in relation to their intrinsic and extrinsic parameters. These simulations represent in our days a necessary complimentary tool for experimental characterization of extrinsic properties of magnetic materials, since they provide information at temporal and spatial scales not accessible experimentally. Recently the micromagnetic simulations have gained a special importance in relation to the study of static and dynamic magnetisation behaviour in lithographed magnetic nanoelements such as magnetic dots, stripes, wires etc. Additionally in our days they provide a method for the magnetic media design, for example, for the optimisation of the magnetic recording media.

The principles of micromagnetics are due to W.F.Brown [1] who derived the micromagnetic equations for the equilibrium properties. The classical (zero-temperature) micromagnetics is a semi-classical approach that considers the magnetisation $\mathbf{M}(\mathbf{r})$ as a vector function of spatial coordinates with constant module M_s . This implies a continuum approximation that ignores any discrete effect. The magnitude M_s is the saturation magnetisation and is defined as a density of magnetic moments (per unit volume of the material). It is useful to work with the unit magnetisation vector $\mathbf{m}(\mathbf{r})=\mathbf{M}(\mathbf{r})/M_s$. The micromagnetic method consists in discretizing the magnetic film in finite differences or finite elements, writing the energy contribution of each magnetic discretization unit, and minimizing the total energy of the system. The total energy comprises the contributions of exchange, anisotropy, Zeeman and magnetostatic energy terms (sgsm units are used):

$$E_{tot} = E_{ex} + E_{ani} + E_Z + E_{demag} , \quad (1)$$

$$E_{ex} = \int_V A(\mathbf{r}) \left[(\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2 \right] dV , \quad (2)$$

where A is the micromagnetic exchange parameter,

$$E_{ani} = -\int_V K(\mathbf{r})[\mathbf{m}(\mathbf{r}) \cdot \mathbf{e}(\mathbf{r})]^2 dV, \quad (3)$$

where K is the macroscopic anisotropy parameter,

$$E_Z = -\int_V (\mathbf{M}(\mathbf{r}) \cdot \mathbf{H}_{ext}(\mathbf{r})) dV, \quad (4)$$

where \mathbf{H}_{ext} is the external applied field,

$$E_{demag} = -\int_V (\mathbf{M}(\mathbf{r}) \cdot \mathbf{H}_{demag}(\mathbf{r})) dV, \quad (5)$$

where \mathbf{H}_{demag} is the demagnetisation field.

The micromagnetism poses particular emphasis on the exact calculation of the demagnetizing field. In the continuous micromagnetic approach it is described by the Maxwell equation in the absence of currents $\nabla \times \mathbf{H}_{demag} = 0$ and, therefore, there exists a potential called scalar magnetostatic potential which satisfies:

$$\mathbf{H}_{demag} = -\nabla U_{mag}. \quad (6)$$

This potential satisfies the Laplace equation outside the material and the Poisson one inside the material:

$$\nabla^2 U_{mag} = 0 \quad \text{Outside ferromagnetic material} \quad (7)$$

$$\nabla^2 U_{mag} = 4\pi \nabla \cdot \mathbf{M}(\mathbf{r}) \quad \text{Inside ferromagnetic material} \quad (8)$$

with the boundary conditions

$$\frac{\partial U_{mag,in}}{\partial \mathbf{n}} - \frac{\partial U_{mag,out}}{\partial \mathbf{n}} = 4\pi \mathbf{M} \cdot \mathbf{n}, \quad (9)$$

where \mathbf{n} is the unit vector normal to the surface of the ferromagnetic sample. The sources of the magnetostatic field are called magnetostatic charges. The surface magnetostatic charge is defined as $\sigma = \mathbf{M} \cdot \mathbf{n}$ and the volume charge as $\rho = -\nabla \cdot \mathbf{M}$. The magnetostatic energy integral extends to all the space, not only the ferromagnetic body, and the minimization of the magnetostatic energy will seek the reduction of the field outside the ferromagnetic body. This can be achieved by reduction of the magnetic charges and that fact is known as the pole avoidance principle. This gives origin to domains and magnetization inhomogeneities such as the ripple structure.

In micromagnetic calculations most of computational time is spent in the evaluation of the magnetostatic field. This interaction is non-local and long-ranged. In the dipole-dipole

approximation the field is a sum of $3N$ elements, where N is the number of individual moments. The direct evaluation of the magnetostatic field scales as $(2N)^2$ and represents too much computational effort. Due to this reason, several advanced methods is currently used for the magnetostatic energy evaluation: Fast Fourier Transform (FFT) [2], finite element/boundary element (FEM/BEM) [3], fast multipole method (FMM)[4] and the dynamic alternative direction implicit (DADI) method [5].

The solution of the variational problem (1) satisfies the Brown condition of equilibrium:

$$\mathbf{H}_{eff} \times \mathbf{M} = 0, \quad \mathbf{H}_{eff} = -\frac{\delta E}{\delta \mathbf{M}} \quad (10)$$

Meaning that in the equilibrium the magnetisation is parallel to the total effective field

$$\mathbf{H}_{eff} = \mathbf{H}_{ext} + \mathbf{H}_{ani} + \mathbf{H}_{ex} + \mathbf{H}_{demag} \quad (11)$$

where

$$\mathbf{H}_{ani} = \frac{2K}{M_s} (\mathbf{m} \cdot \mathbf{e}) \mathbf{e}, \quad \mathbf{H}_{ex} = \frac{2A}{M_s} \nabla^2 \mathbf{m} \quad (12)$$

It is often convenient to define the anisotropy field $H_K=2K/M_s$ and normalize all the fields to this parameter.

In numerical approaches we divide or discretize the sample by the discretization length Δ considering a constant magnetisation inside each element. There are two physically relevant parameters that we need to take into account in order to select the size of discretization length Δ :

The domain wall-width parameter (defining the width of the Bloch wall, found in hard magnetic materials):

$$\delta_w = \pi \sqrt{\frac{A}{K}} \quad (13)$$

and the *exchange correlation length* (defining the Néel domain wall width typical for soft magnetic materials)

$$l_{ex} = \sqrt{\frac{A}{M_s^2}}. \quad (14)$$

In order to describe correctly the domain wall the discretization length must be less than its width but include enough atoms to ensure the continuum approximation.

The energy (1) could be directly minimized using, for example, the conjugate-gradient method. However, it has become custom to use the integration of the dynamical equation of

motion as the minimization procedure. The dynamics is described by the Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{d\mathbf{M}_i}{dt} = -\frac{\gamma}{1+\alpha^2}(\mathbf{M}_i \times \mathbf{H}_{eff,i}) - \frac{\alpha\gamma}{(1+\alpha^2)M_s} \mathbf{M}_i \times (\mathbf{M}_i \times \mathbf{H}_{eff,i}) \quad (15)$$

where i is the discretization element index, α is the damping parameter (which represents a phenomenological relaxational mechanism) and γ is the gyromagnetic factor. The damping parameter is normally in the range $\alpha=0.01$. Numerical integration of Eq.(15) provides a dynamical information, including the magnetisation precession around the total magnetic field.

Alternatively for the energy minimization procedure one can use large values $\alpha=1.0$.

In our days there exist several commercial and publicly available micromagnetic codes. Among the public codes the most used are the following:

OOMMF (object-oriented micromagnetic framework). This code is a public domain micromagnetic program developed at the National Institute of Standards and Technology (NIST), USA. The code uses finite-difference discretization and FFT for magnetostatic field calculations. It can run under both Unix and Windows platforms.

Visit: <http://math.nist.gov/oommf/>

MAGPAR: finite-element micromagnetic code with FEM/BEM method to calculate magnetostatic fields, created by Vienna University of Technology and Werner Scholtz. Works under Linux platform.

Visit: <http://magnet.atp.tuwien.ac.at/>

NMAG: micromagnetic simulation package based on finite elements created by H.Fanghor (University of Southampton, UK), finite-element based.

Visit: <http://nmag.soton.ac.uk/nmag>

The present tutorial will be based on the OOMMF code. We will give a quick overview of the oommf possibilities. Several examples will be considered:

We will aim at micromagnetic modelling of a permalloy magnetic nano-sized dot. We will calculate several dynamical problems: (i) the magnetization precession around constant field from which we will evaluate the precessional frequency and (ii) the magnetisation switching under external applied field. Finally we will calculate the magnetisation configuration in the form of a vortex structure (see Figure below).

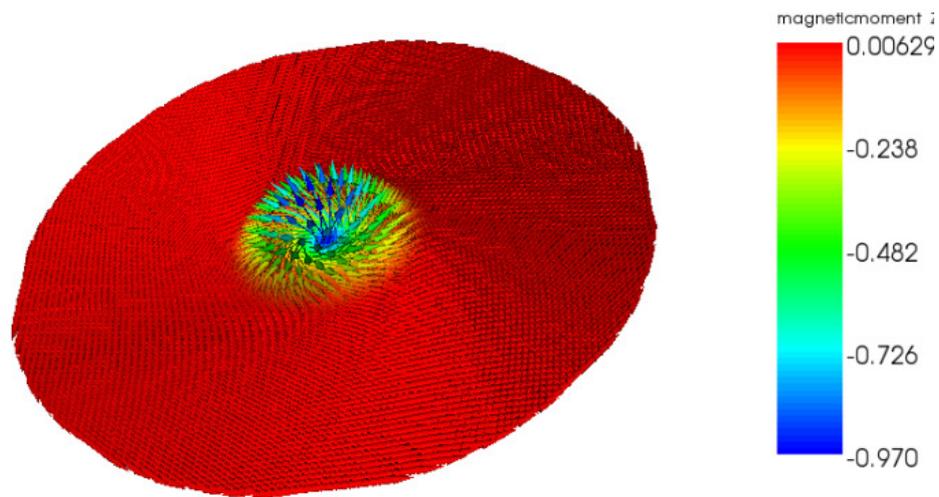


Fig.1 Minimum magnetic configuration in the form of magnetic vortex in a permalloy disc obtained by oommf simulation.

References

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