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Proposal of a micromagnetic standard problem for ferromagnetic resonance simulations

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ABSTRACT

Nowadays, micromagnetic simulations are a common tool for studying a wide range of different magnetic phenomena, including the ferromagnetic resonance. A technique for evaluating reliability and validity of different micromagnetic simulation tools is the simulation of proposed standard problems. We propose a new standard problem by providing a detailed specification and analysis of a sufficiently simple problem. By analyzing the magnetization dynamics in a thin permalloy square sample, triggered by a well defined excitation, we obtain the ferromagnetic resonance spectrum and identify the resonance modes via Fourier transform. Simulations are performed using both finite difference and finite element numerical methods, with OOMMF and Nmag simulators, respectively. We report the effects of initial conditions and simulation parameters on the character of the observed resonance modes for this standard problem. We provide detailed instructions and code to assist in using the results for evaluation of new simulator tools, and to help with numerical calculation of ferromagnetic resonance spectra and modes in general.

1. Introduction

Computational micromagnetics is a well developed field that sees widespread use in both modern physics and magnetic device engineering communities [1–3]. With the advancement of micromagnetic models, simulation techniques, and processing power, the list of phenomena that can be studied has grown substantially and includes such diverse fields as the spin transfer torque [4] and spin wave dispersion in magnonic crystals [5]. An essential equation in most of the micromagnetic system models [6] is the Landau–Lifshitz–Gilbert (LLG) equation – a differential equation governing the magnetization dynamics. However, this equation can be analytically solved only for a very limited number of systems and, because of that, the complexity of common problems requires the use of micromagnetic simulation packages such as OOMMF [7], LLG Micromagnetics, [8] Micromagnum [9], and Mumax [10], which use the Finite Difference (FD) approach, and Nmag [11] and Magpar [12], employing the Finite Element (FE) approach to spatial discretization. To compare this range of numerical solvers, as well as to evaluate their validity and reliability, NIST's Micromagnetic Modelling Activity Group (μMag) publishes standard problems [13–15]. Recent additions have included the spin transfer torque [4] and the spin wave dispersion [16] standard problems. In the light of this, it is natural to extend the coverage of standard problems in order to include the FerroMagnetic Resonance (FMR), a technique closely associated with many practical uses ranging from material characterization to the study of spin dynamics [17].

FMR probes the magnetization dynamics in samples using microwave fields. The absorption of the applied microwave field is at its maximum when the microwave's frequency matches the frequency of the studied system's resonant modes. By analyzing the resonance modes as a function of an applied magnetic field, some material parameters, such as the Gilbert damping and magnetic anisotropy constants, can be determined [17]. This makes FMR a powerful technique in the characterization of ferromagnetic nanostructures; including measurements of spin pumping [18] and exchange coupling [19]. In a typical experiment, microwaves are directed across the sample using a coplanar waveguide, and their transmission is measured as a function of both

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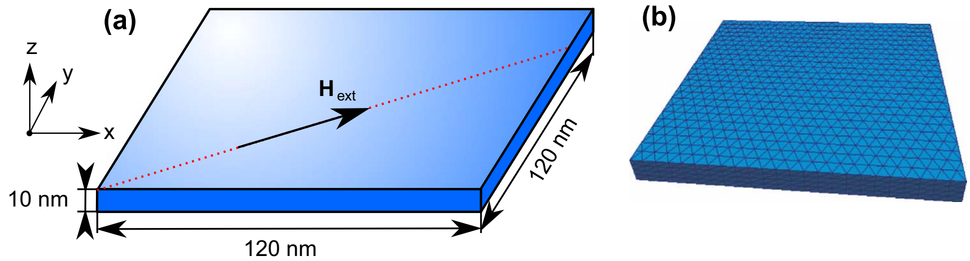

Fig. 1. (a) Geometry of the thin film sample, showing the static bias field $\mathbf{H}_{\text{ext}}$. The field is slightly off-diagonal to break the symmetry of the system and thus avoid degenerate eigenmodes. (b) Illustration of the mesh used for the finite element approach. The discretization for the finite difference approach is to divide the system into cubes with 5 nm edge length, resulting in $24 \times 24 \times 2$ cubes (not shown).

external bias field and excitation frequency [20].

In terms of computational micromagnetics, there are at least three methods that can be used to simulate the FMR:

1. Application of a time-dependent periodic sinusoidal magnetic microwave field of fixed frequency f to determine the magnetization precession amplitude in response to the system. If the precession amplitude is small, the power absorption of the microwave field would be small as the excitation frequency does not couple well to the set of natural frequencies of the system. This method is conceptually simple but computationally very demanding as, for every frequency f, the micromagnetic simulation needs to compute the time evolution of the system's magnetization after the transient dynamics has been damped and steady magnetization precession is reached. This will only provide one point on the frequency–absorption curve and only a micromagnetic simulation software that supports a time dependent external magnetic field can be used.
2. Ringdown method [21]: the system is perturbed from its equilibrium state by applying a short-lived and sufficiently weak excitation, followed by simulation and recording of the magnetization dynamics. Resonance frequencies and corresponding modes are extracted by performing the Fourier transform on the recorded data. This is an efficient way to determine the eigenmodes of the system.
3. Eigenvalue method [22]: instead of simulating the time evolution of the system's magnetization as in the methods above, the problem is represented as an eigenvalue problem, whose solutions provide the frequencies (eigenvalues) and mode shapes (eigenvectors) of the system. This method requires specialist software that is not widely available.

Our goal is to establish a standard problem to serve as a benchmark against which future simulation tools and computational studies of the FMR can be compared and validated. In this standard problem proposal, we will follow the second (ringdown) method, which is supported by most micromagnetic packages and compare its output with the third (eigenvalue) method. We provide a detailed standard problem description and specification as well as the complete set of computational steps and code repository [23] in order to make it easily reproducible and accessible to a wide community. Parts of the code repository can also be used as an example to compute FMR data and modes from micromagnetic simulations. It is hoped that this work will aid the development of micromagnetic simulations of systems undergoing FMR and support and drive experimental efforts.

Section 2 introduces and motivates the choice of the FMR standard problem, and introduces the frequency spectrum computed in different ways. Section 3 provides a more detailed discussion including computation of the normal mode shape, the eigenvalue problem approach as an alternative way of computing the frequency spectrum and normal modes, and a systematic study of the dependence of the results on variations in the simulation parameters such as damping, relaxation of the initial state, nature of the perturbation and mesh discretization. We close with a summary in Section 4. The Appendix provides more details on parameters used in the Nmag simulations, the eigenvalue approach and simulation results obtained in the absence of demagnetization effects.

2. Selection and definition of standard problem

2.1. Problem definition

We choose a cuboidal thin film permalloy sample measuring $120 \times 120 \times 10\ \text{nm}^3$, as shown in Fig. 1(a). The choice of a cuboid is important as it ensures that the finite difference method employed by OOMMF does not introduce errors due to irregular boundaries that cannot be discretized well [24]. We choose the thin film geometry to be thin enough so that the variation of magnetization dynamics along the out-of-film direction can be neglected. Material parameters based on permalloy are shown in Table 1. An external magnetic bias field $\mathbf{H}_{\text{ext}}$ with magnitude $H_{\text{ext}} = 80$ kA/m is applied along the direction $\mathbf{e} = (1, 0.715, 0)$ (at 35.56° to the x-axis), i.e., $\mathbf{H}_{\text{ext}} = H_{\text{ext}} \cdot \mathbf{e}/|\mathbf{e}| \approx (65.1, 46.5, 0)$kA/m as shown in Fig. 1(a). We choose the external magnetic field direction slightly off the sample diagonal in order to break the system's symmetry and thus avoid degenerate eigenmodes.

First, we initialize the system with a uniform out-of-plane magnetization $\mathbf{m}_0 = (0, 0, 1)$. The system is allowed to relax for 5 ns in the presence of $\mathbf{H}_{\text{ext}}$, which was found to be sufficient time to obtain a well-converged equilibrium magnetization configuration. We refer to this stage of simulation as the *relaxation stage*, and its final relaxed magnetization configuration, as shown in Fig. 2, is saved to serve as the initial configuration for the next *dynamic stage*. Conceptually, what is required to find the relaxed state is to minimize the system's energy in the presence of an

Table 1
External magnetic fields and material (permalloy) parameters used. Where these change between the initial relaxation stage of the simulation, and the subsequent dynamic stage, both values are shown.

Parameter	Value	Unit
Saturation magnetization (M_s)	800	kA/m
Exchange constant (A)	1.3×10^{-11}	J/m
Anisotropy constant (K)	0	J/m^3
Gyromagnetic ratio (γ^*)	2.210173×10^5	m/(As)
Gilbert damping (α), relaxation	1.0	
Gilbert damping (α), dynamic	0.008	
DC bias field magnitude ($\lvert\mathbf{H}_0\rvert$)	80	kA/m
DC bias field ($\mathbf{e}$), relaxation	[1, 0.715, 0]	
DC bias field ($\mathbf{e}$), dynamic	[1, 0.7, 0]	