Computational Modeling of Magnetic Hysteresis in Nanoparticles and Ultrathin Films

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We present recent results from computational studies of magnetic hysteresis in nanoparticles and ultrathin films with uniaxial and biaxial anisotropy, which are exposed to time-varying magnetic fields. The microscopic switching mechanism influences the dependence on particle size and temperature of quantities such as the coercivity and the switching field. In certain parameter ranges interesting dynamical effects, including stochastic resonance and a dynamic phase transition, are observed. Potential technological applications include ultrahigh density magnetic recording media. All analysis presented here is also applicable to experimental data.

1 Introduction

The problem of thermal magnetization reversal is an important issue for the nanoscale ferromagnets that will find widespread application in future devices. Here we focus on single-domain nanoscale magnets with large axial anisotropy exhibiting hysteresis in a periodic magnetic field. For uniaxial ferromagnetic particles after a sudden field reversal, the primary reversal mode depends on the interplay of the length scales associated with the particle size and supercritical droplets of the preferred orientation, formed from thermal fluctuations in the metastable background. The size that fluctuations must reach before growth becomes energetically favorable — the critical droplet size — decreases as the field increases.[1] For magnetic particles smaller than this, subcritical fluctuations can reverse the magnetization. Magnets larger than a critical droplet, but smaller than the typical droplet separation, are switched by the random nucleation of a single droplet followed by its rapid growth until it occupies the entire system [single-droplet (SD) regime]. For magnets significantly larger than the typical droplet separation, the system is self-averaging: many supercritical droplets form and contribute to the decay of the metastable phase [multidroplet (MD) regime]. These two decay modes also imply qualitatively different hysteretic behaviors in nanoscale ferromagnets when a periodic magnetic field is applied.[2,3]

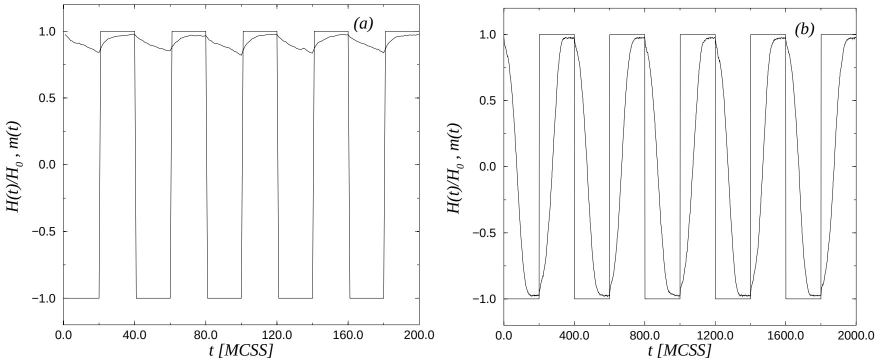

Figure 1: Short segments of time series showing the magnetization $m(t)$ and the applied field $H(t)$ for a 128×128 kinetic Ising model. (a) $t_{1/2} = 0.27\langle\tau(H_0)\rangle$; (b) $t_{1/2} = 2.7\langle\tau(H_0)\rangle$.

2 Uniaxial Models

The 2D kinetic Ising model in a sinusoidally oscillating magnetic field of amplitude H_0 is suitable to model hysteresis in ultrathin uniaxial ferromagnetic films. It has been studied extensively for both decay regimes.[2,3] Here, hysteresis is a competition between two time scales: the average lifetime of the metastable phase following an instantaneous field reversal from $+H_0$ to $-H_0$, $\langle\tau(H_0)\rangle$, and the half-period of the external driving field, $t_{1/2}$.

In the SD regime the lifetime is stochastic, i.e., the standard deviation of $\tau(H_0)$ is comparable to its mean. The analogous quantity with an oscillating field is the time between zero-crossings of the magnetization, called the residence-time. The study of the residence-time distribution reveals clear signs of *stochastic resonance*, *i.e.* , there is a range of low frequencies where $m(t)$ is essentially synchronized with $H(t)$.[2]

With MD switching, the relative standard deviation of $\tau(H_0)$ is much smaller than unity (the system is self-averaging), and a completely different behavior is observed: the system exhibits a *dynamic phase transition* as $t_{1/2}$ is varied.[3] A suitable order parameter is the period-averaged magnetization, Q. For $t_{1/2} \ll \langle\tau(H_0)\rangle$, the system does not have time to switch, resulting in $Q \neq 0$ (dynamic ordered phase), while for $t_{1/2} \gg \langle\tau(H_0)\rangle$ it switches every half period and $Q = 0$ (dynamic disordered phase). The transition between the high- and low-frequency regimes is sharp,[3] indicated by a singular “susceptibility,” defined to be proportional to the scaled variance of Q.

Here we present new results at $0.8T_c$ for a square-wave external field and H_0=$0.3J$, where J is the nearest-neighbor coupling constant. The shape of the

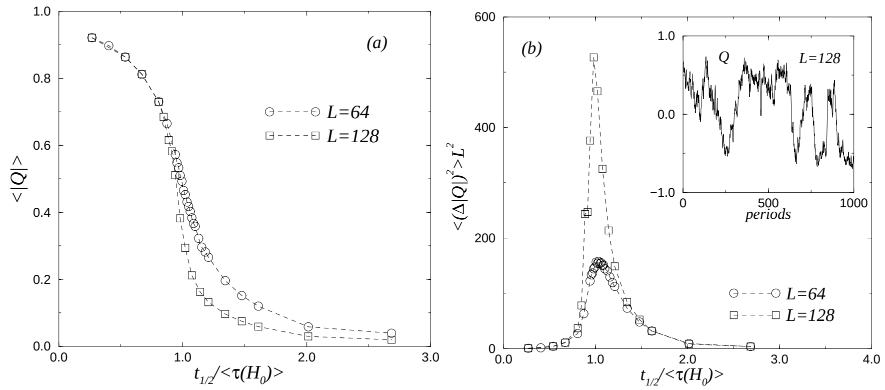

Figure 2: Order parameter Q (a) and "susceptibility" (b) vs scaled period of the applied field for model of Fig. 1. The inset in (b) shows the critical fluctuations of Q for part of a simulation near the transition.

applied field does not change the qualitative behavior: the high- (Fig. 1a) and low-frequency (Fig. 1b) regimes are separated by a sharp transition, clearly indicated by the finite-size scaling of the order parameter Q (Fig. 2a) and its scaled variance (Fig. 2b). Further study of the *local* period-averaged magnetization shows that there indeed exists a divergent length scale, associated with the divergent order parameter fluctuations near the transition.

3 More Complicated Models

Uniaxial anisotropy as extreme as the Ising model is rare in magnetic materials. One generalization is to consider systems with two anisotropy axes modeled by the four-state clock model.[4] A typical time series in the high-frequency MD regime is shown in Fig. 3a. This is for the same parameters as Fig. 1a ($L = 128$, $H_0 = 0.3\,J$, $T = 0.8\,T_c$, no asymmetry), so they can be directly compared.

A different generalization is micromagnetic models based on precession of fixed-length spins under local fields due to the applied field, exchange interactions, and dipole-dipole interactions. Thermal fluctuations are incorporated into the Landau-Lifshitz equation of motion by a Langevin term which obeys a fluctuation–dissipation relation.[5] The simulations are computationally intensive, but with strong shape anisotropy the behavior is similar to other anisotropic models. The high-frequency time series shown in Fig. 3b is for a simulated $20\,\text{nm} \times 20\,\text{nm} \times 400\,\text{nm}$ iron nanopillar with $H_0 = 200\,\text{Oe}$ and $T = 10\,\text{K}$. It is qualitatively similar to the others.

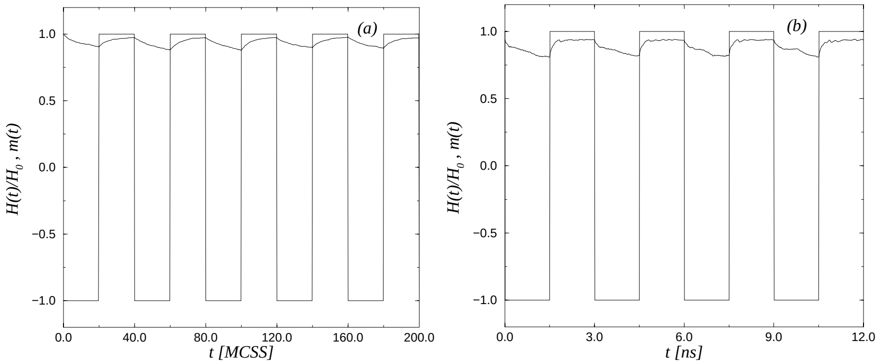

Figure 3: Time series of the magnetization $m(t)$ and the applied field $H(t)$ at high frequency for (a) four-state clock model and (b) micromagnetic simulation.

4 Conclusions

The thermally activated behavior of nanoscale magnets in periodic applied fields has been investigated for cases of strong anisotropy. The size of the magnet compared to the critical droplet size and the typical droplet separation for a given field governs the dynamic response to changes in field. For small nanomagnets stochastic resonance is found, while for larger ones a dynamic phase transition occurs as the period of the applied field is changed. Simulations for other models of magnetic materials indicate these to be universal phenomena.

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