Journal of Magnetism and Magnetic Materials 361 (2014) 140–149

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

An analytical model for vortex core pinning in a micromagnetic disk

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ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form
12 February 2014
Available online 1 March 2014

Keywords:
Magnetic vortex
Pinning
Micromagnetic modeling

ABSTRACT

A two-parameter analytical model is constructed to describe a thin, magnetically soft, circular disk in the vortex state. The model is capable of describing the change in evolution of net magnetization and of vortex core position when the core interacts with a magnetic pinning site. The basis of the two-parameter model is formed by a piecewise, physically continuous, magnetization distribution constructed with two regions described by different one-parameter models. Benchmarking against numerical simulations of ideal disks with and without pinning sites shows that the model provides accurate predictions of magnetization, hysteretic transitions, and 2-D displacement of the vortex core in the presence of pinning sites. The demonstrated accuracy of the model supports its use as an empirical tool to extract quantitative maps of vortex pinning energies from measurements of magnetization.
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1. Introduction

Interest in magnetic vortices [1,2] in thin disks has grown dramatically over the past two decades. Topological structures such as vortices are stable, manipulable objects that show promise as logic elements or storage media in spintronics applications [3]. The thin soft magnetic disk, the prototypical system containing a vortex, has therefore been subject to extensive investigation. Properties studied include structure [4,5], dynamical modes [6–8], annihilation [9,10], and creation [9,11–13]. As each aspect of vortex physics is probed experimentally, and considered for technological applications, theoretical understanding via simulation and modeling is also advanced. Modeling is particularly important in the case of the thin ferromagnetic disk as it presents a well-defined system amenable to description by an analytical approach.

Extension of analytical models to include pinning effects has gained increasing importance. The interaction of vortex cores or domain walls with film inhomogeneities has been a topic of significant recent interest. Geometric defects or magnetic impurities can increase or decrease the energetic cost of the topological magnetic structures [14], creating preferential locations for domain walls or otherwise altering the magnetization distribution. In the disk system, direct observations of vortex state pinning have been made with Lorentz microscopy [15] while the effect on vortex gyration has been observed with time-resolved magneto-optical Kerr effect microscopy [16–19] and electronic techniques [20]. Incorporation of pinning potentials into existing analytical models has permitted a qualitative description of the position of the vortex and its reduced displacement susceptibility [21]. This approach, however, is insufficient for quantitative applications. Recent work using nanomechanical torque magnetometry has provided direct observation of the Barkhausen steps associated with jumps in core position [22]. Quantitative analysis of these results necessitates the development and benchmarking of a model that permits a quantitative description of both net disk magnetization and vortex core position in the presence of pinning effects. To accomplish this, the potential for evolution of the magnetic moment of the outer regions of the disk, decoupled from the vortex core position, must be acknowledged. A two-parameter description permits the inclusion of a dipole-exchange spring coupling of the core to a parameterized outer magnetic moment. Presented here is a detailed description of the construction of the two-parameter model and verification of its accuracy against numerical simulations of magnetic vortices in disks featuring pinning sites.

1.1. The vortex state and existing models

In zero field, the vortex state in a disk represents the ground state configuration for a wide variety of disk aspect ratios. Over most of the disk, a circularly symmetric in-plane magnetization distribution maintains magnetization tangential to the disk boundary and reduces dipolar energy. This necessitates a higher exchange energy relative to the uniformly magnetized state, and results in an out-of-plane magnetized core at the disk center

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http://dx.doi.org/10.1016/j.jmmm.2014.02.078
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featuring high energy density. For clarity, the in-plane region outside of the core is referred to as the skirt. Analytical models of the vortex state aim to describe the net energy and magnetization in terms of a reduced set of parameters, often vortex core position. This description immediately implies the potential for an empirical ruler to extract core position from magnetization, providing a practical motivation for models with high accuracy.

The zero-field vortex state ansatz was first developed for the magnetic disk by Aharoni [23]. Further work by Usov and Peschanny [4] determined an exchange optimized functional form of the core magnetization profile exhibiting good agreement with simulation [24] and experimental observations [5]. Computation of the evolution of the state with field presents a more challenging problem. Extended models built on this initial work use simplifying assumptions to compute magnetization distributions with a displaced core. The Rigid Vortex Model (RVM) considers the displacement of the core under the assumption that the magnetization distribution developed by Usov and Peschany simply translates rigidly relative to the disk boundary, remaining circularly symmetric around the core [25,26]. Magnetization distributions that look more realistic may be computed by minimization of the exchange energy using prescribed boundary conditions; this leads to the so-called Two Vortex Model (TVM) [27,28]. The assumptions about rigidity or boundary conditions lend particular strengths to each type of model: higher order versions of the RVM provide effective descriptions of the magnetic susceptibility of the displaced vortex [10], while the TVM provides a good description of low field vortex core dynamics [29–31]. The RVM and TVM make critical contributions to the two-parameter model discussed here and, therefore, are introduced in the following sections. An additional modification to the RVM is also introduced that significantly improves its performance.

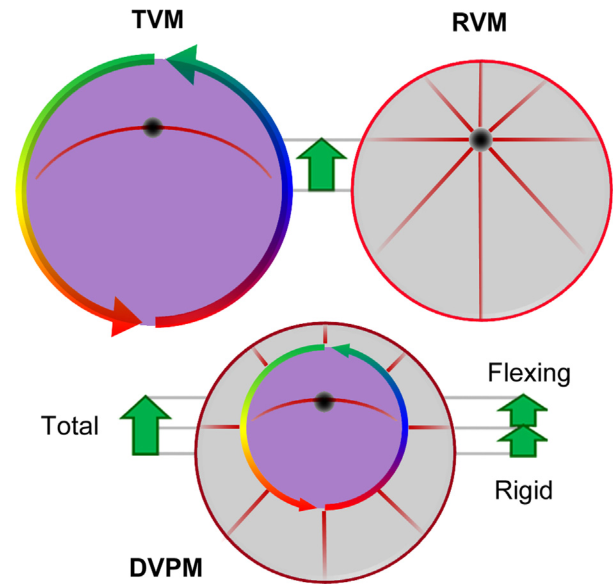

Fig. 1. Schematics depicting the evolution of the magnetization distribution as the vortex core is displaced for various analytical models. The red lines indicate contours of constant $|M_y|$ magnetization while the color gradient circular arrows indicate an in-plane tangential boundary condition for the magnetization. The TVM holds a tangential boundary condition as the vortex core is displaced. The RVM simply translates the circularly symmetric zero field magnetization distribution relative to the disk. The DVPM incorporates a central flexible TVM-described region into an RVM-described annulus in creating a piecewise continuous magnetization distribution. Major energetic contributions arise from the demagnetization charges computed in each model. In the TVM, only volume demagnetization charges are present (purple shading). In the RVM, only edge demagnetization charges are accounted for (red line). In the DVPM both are present. Consequently, since the RVM parameterizes all demagnetization charges as edge charges, the computed density of edge charges of the RVM annulus must be modified for use in the DVPM. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

2. Theory

2.1. The rigid vortex model

The RVM is derived by considering the zero field vortex magnetization distribution [23,4] to be immutable, and then translating that distribution relative to the physical boundary of the disk [25,26] (Fig. 1). To solve the model, the energetic contributions from demagnetization charges, exchange and the applied field must be computed in terms of the core position. Here, a soft anisotropy free material will be considered. In terms of the reduced field, $h = H/M_S$, the 3rd order expression for the total normalized energy of a disk with a radius R and thickness L described by the RVM [10] may be expressed as

$$\frac{E_{tot}}{\mu_0 M_s^2 V} = \frac{\beta}{2} b^2 - h\left(b - \frac{b^3}{8}\right), \tag{1}$$

where the normalized core displacement $s = \Delta r/R$ is equal to b, V is the disk volume, $\beta = F(L,R) - R_0^2/R^2$ is a constant describing the demagnetization energy and exchange energy with $R_o = \sqrt{2A/\mu_o M_S^2}$ denoting the exchange length. In the derivation of the RVM, the factor $F(L,R)$ is found to be equal to the demagnetization factor for a disk uniformly magnetized in plane [25].

Some consideration must be given to this factor in the context of a disk made of a soft magnetic material. Any inspection of displaced vortex magnetization distributions in simulated disks composed of permalloy or a similar soft material reveals the rigid assumption is flawed (Fig. 2). The magnetic moments near the boundary of the disk will always rotate to a certain degree to partially maintain a tangential boundary condition and lower the

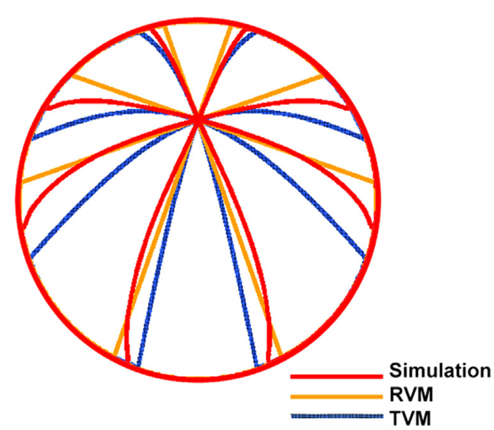

Fig. 2. Contours of constant magnetization aid visualization and comparison of the magnetization distributions predicted for a displaced vortex core by the RVM and the TVM with no side charges, against simulation. Of critical importance is the fact that the TVM contours lag behind the contour lines of the simulation everywhere, indicating an underestimate of the total magnetic moment. By contrast the RVM contours lead and lag the simulation contours, indicating a smaller error in the computed total magnetic moment. Here the contours for $|M_y/M_S| = 0.4$ and 0.8 are shown, compared against a simulation for a disk with a diameter of 1 μm, and thickness of 40 nm. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

total demagnetization energy by redistributing uncompensated edge dipoles into the volume. In computation of the energy of uniformly magnetized particles, it is possible to account the net reduction by solving for the magnetic potential at the disk boundary taking into account a discontinuity in the rotational susceptibility of the material inside and outside of the disk. The

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