Effect of Thermal Fluctuations on the Performance of Particulate Media

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Micromagnetic simulations are used to evaluate the effect of thermal fluctuations on the performance of perpendicular BaFe media. The write simulations are performed using a highly efficient particle micromagnetic solver running on graphics processing units. Thermal effects are found to reduce the field required to write optimally the medium, in agreement with the decay of the medium mean switching field with temperature. Thermal fluctuations also affect the system write performance: a broadband signal-to-noise ratio (BB-SNR) loss of several decibels is observed for a recording temperature of 400 K compared to the 0 K case. The SNR correlates with the increase of the written transition width and relates to the broadening of the medium switching field distribution at increasing recording temperatures. The presented results are also relevant for understanding thermal effects in granular media used in magnetic recording.

***Index Terms*—Magnetic recording, magnetic tape recording, micromagnetic simulations, thermal fluctuations.**

I. Introduction

MAGNETIC tape storage is the technology of choice for data backup and archive applications. With the explosion of digital data created each year, the need for such reliable and cost-effective archival solution will continue to persist. Today's state-of-the-art tape-drive systems provide a storage capacity of 4–5 TB per tape cartridge, corresponding to an areal density of about 3 $\mathrm{Gb/in^2}$. The magnetic medium is particulate, consisting of a nonoriented assembly of barium ferrite (BaFe) particles embedded in a polymer matrix [1]. Particulate media are still preferred in tape systems because continuous improvements in particle synthesis and coating technology have maintained a sizeable cost advantage over evaporated or sputtered tape media [2], [3]. Recently, a recording density of 29.5 $\mathrm{Gb/in^2}$ was demonstrated by using a perpendicularly oriented medium with finer (1600 $\mathrm{nm^3}$) BaFe particles [4]. The composition of the smaller BaFe particles was tuned to increase their anisotropy constant K and thereby maintain a thermal stability factor $\mathrm{KV/k_BT}$ around 70 [5]. Maintaining $\mathrm{KV/k_BT}$ above 60 is a well-known requirement in magnetic recording: it ensures enough magnetization stability for long-term data retention in spite of thermal fluctuations. However, thermodynamics still impact the system performance during the write process. As micromagnetic simulations for perpendicular recording media have shown, thermal fluctuations degrade the quality of the written transitions [6], [7] and, therefore, limit achievable areal densities. Write errors induced by thermal fluctuations become even more significant for recording schemes that include a write assist mechanism [8].

In this work, we use micromagnetic simulations to quantify the effect of the recording temperature on the signal-to-noise-ratio of BaFe particulate tape media. The write simulations are performed with a highly efficient particle micromagnetic solver that is described in Section II. The structure and magnetic properties of the 29.5 $\mathrm{Gb/in^2}$ BaFe medium were used in the calculations. Our results show that thermal fluctuations impact significantly the recording performance of the particulate medium. They should be properly accounted for when assessing the recording limits of particulate media. The presented results are also of direct relevance for understanding the performance of granular media in magnetic recording.

Manuscript received October 26, 2012; accepted January 10, 2013. Date of current version July 15, 2013. Corresponding author: P.-O. Jubert (e-mail: pjubert@us.ibm.com).

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Digital Object Identifier 10.1109/TMAG.2013.2241740

II. Particle Micromagnetic Solver

Write simulations are performed using an efficient particle micromagnetic solver, which is a derivation from the FastMag simulator [9]. The solver solves the Landau–Lifshitz–Gilbert equation for generally shaped particles assuming that they are small enough so that their magnetization is essentially uniform. The particles are introduced via a volumetric or surface mesh and are represented by a single spin per particle. This representation produces the smallest number of unknowns, eliminates the need for computing exchange fields, and results in a nonstiff system for time integration. The magnetostatic field is computed by separating the interparticle interactions into near- and far-field components. The near-field components are computed by direct tensor superposition via double surface integrals for particles located within a prescribed (relatively small) near-field distance between each other. The far-field magnetostatic interactions generated by the particles outside the near-field distance are accounted for via the magnetic dipole approximation. The computation of the most time consuming far-field components is accomplished using highly efficient implementations of the nonuniform grid interpolation method with the computational complexity of O(N) [9], [10] or nonuniform FFT method/adaptive integral method with the computational complexity of O(N log N) [11], where N is the number of particles. The methods are implemented on massively parallel graphics processing units (GPUs) with 100–200 speed-ups as compared to the same methods implemented on central processing units (CPUs). As an example, a single field evaluation for the case of $\mathrm{N} = 1\mathrm{e}6$ takes about 0.2 s on Nvidia GeForce GTX 680 GPU. Thermal fluctuations are introduced as a stochastic thermal field.

III. Particulate Properties and Recording Parameters

The particulate medium considered for this work follows the structure and properties of the 29.5 $\mathrm{Gb/in^2}$ BaFe medium [4].

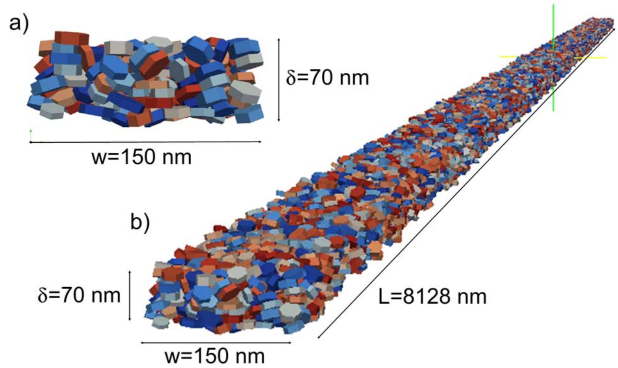

Fig. 1. Illustration of a, 8-μm-long, 150-nm-wide, 70-nm-thick BaFe particulate media slab used in the write simulations. (a) Side view, (b) perspective view.

Its three dimensional random structure is generated with Bulletpack, a custom made particle packing algorithm that mimics the experimental fabrication process [12]. A dilute assembly of particles is first created by random sequential addition and then compressed using gravity-like forces and rigid-body dynamics. During the compression stage (equivalent to the drying stage), an out-of-plane orienting magnetic field is applied that exerts a torque on the particles and allows controlling the degree of perpendicular orientation of the medium [13]. The BaFe particles are hexagonal platelets with a mean volume of 1600 nm^3 and a mean diameter to thickness aspect ratio of 3. The particles' volume and aspect ratio distributions are Gaussian with $\sigma_V/\langle V\rangle = 0.3$ and $\sigma_{\mathrm{AR}}/\langle \mathrm{AR}\rangle = 0.2$.

Fig. 1 shows the structure of a calculated medium. Its thickness (70 nm on average), its volume packing fraction (44%) and its orientation distribution all match those of the experimental medium [4]. The intrinsic in-plane and out-of-plane squareness values are 0.24 and 0.89, respectively. The particles' saturation magnetization is 250 emu/cc. The crystalline easy axis is the hexagonal axis of the platelets and the mean anisotropy constant is 1.5e6 erg/cc with a normal distribution characterized by $\sigma_K/K = 0.150$. These values are determined by reproducing experimental hysteresis loops and remanence curves [13], [14].

Recording simulations are performed with the particle micromagnetic solver described above using 8128-nm-long and 150-nm-wide media slabs generated with different random seeds. Each media slab comprises close to 23 000 particles. The write head is moving at 10 m/s over the medium and record periodic waveforms at 250 and 500 kfci. The writer has a ring geometry with a 200-nm-long gap and its write fields are modeled using the Szczech approximation [15]. The head-media spacing, d, is set to 24 nm. To simulate the finite rise time of the write field, the deep-gap field changes with time, t, according to

$$H_g\left(n\frac{p}{2}<t<(n+1)\frac{p}{2}\right)=(-1)^n H_g^0\left[1-2.erf\left(\frac{t-np/2}{\frac{\tau}{2}}\right)\right] \quad (1)$$

where n is integer, p is the signal period, $\mathrm{H_g^0}$ is the optimum deep-gap field, and τ characterizes the switching rise time. For all simulations presented here we used $\tau = 0.2$ ns.

Readback waveforms are calculated using the reciprocity principle and double Karlqvist fields to approximate a shielded magnetoresistive sensor [16]. The shield-to-shield distance is 100 nm and the head-media spacing is 24 nm. Eventually, signal spectra with a resolution bandwidth of $61.5\mathrm{e} - 6\ \mathrm{nm}^{-1}$ are obtained by averaging three fast Fourier transforms (FFT) of three different 16.2-μm-long readback waveforms [13], [14]. Two 8128-nm-long recorded media slabs are concatenated end-to-end before calculating the readback signal. From these signal spectra, we can evaluate the medium noise with reasonable statistics and extract the recorded signal amplitude and the broadband signal ratio as a function of the write frequency and recording temperature.

IV. Results and Discussion

First, the best write condition is determined for each recording temperature T. Write simulations are performed at 250 kfci for increasing values of the writer deep-gap field $\mathrm{H_g^0}$. After FFT of the readback signals, the evolution of the signal amplitude as a function of $\mathrm{H_g^0}$ is obtained. Fig. 1(a) shows the resulting bell-shape curves for different recording temperatures (from 0 to 400 K). The best possible write field is the one that maximizes the signal output. Smaller and larger $\mathrm{H_g^0}$ values result in degraded field gradients at the written transition location and, for the smallest $\mathrm{H_g^0}$ values, in incomplete writing of the thick medium. Fig. 1(b) shows that the optimum deep-gap field $\mathrm{H_g^0}$ decreases with increasing the recording temperature. This is expected and is related to the reduction of the medium mean switching field with T.

The evolution of a medium coercivity with temperature (and therefore the evolution of $\mathrm{H_g^0}$ with T) can be described from Sharrock's law [17], [18]

$$H_{sw}(T,t_{\mathrm{eff}}) = H_k\left\{1-\left[\left(\frac{k_B.T}{K_1.V}\right).\ln\left(\frac{t_{\mathrm{eff}}.f_0}{\ln(2)}\right)\right]^{\frac{1}{n}}\right\} \quad (2)$$

where k_B is the Boltzman constant, $f_0 = 1\mathrm{e}9$ Hz is the attempt frequency and n in the exponent depends on the medium easy axis orientation. For the imperfectly oriented medium considered here, we assume $n = 3/2$ [18]. In (2), t_{eff}, is an effective measurement time during which a stationary field is applied to the medium. During the recording process, the particles in the medium rather experience a variation of field amplitude. One could consider instead dynamic coercivity expressions for a field sweeping at a constant rate R [19]–[21]. Feng and Visscher derived a general expression relating R and the switching field [20]

$$R = \frac{1}{\ln(2)}\frac{f_0 H_k}{s}\int_y^{\infty}\exp(-y'^n)dy' \quad (3)$$

with $s = (K_1.V/k_B.T)^{1/n}$ and $y = s[1-H_{sw}(T)/H_k]$. Using (2) and (3), we obtain reasonable agreements for the evolution of $\mathrm{H_g^0}$ with T for the fitting parameters $t_{\mathrm{eff}} = 3$ ns and $\mathrm{R} = 2\mathrm{e}11$ Oe/s, respectively [see Fig. 2(b)]. The effective field rate can be compared to the product of the writer effective field gradients at the write location, dH_{eff}/dx, times the tape velocity. The effective field is $H_{\mathrm{eff}} = |\vec{H}_{\mathrm{head}}(x)|/H_{sw}(\theta_H(x))$. For Szczech head fields, at 1/2 the medium depth and for $\mathrm{H_g^0/H_k} = 0.9$, we calculate dH_{eff}/dx is 6.9e6 $\mathrm{H_k/m}$. Multiplying by the tape velocity gives a maximum expected field rate of 8e11 Oe/s at $\mathrm{T} = 0$ K, which is close to the fitted R value. Note that (3) assumes the effective field rate to be independent of the recording temperature, which is only an approximation as dH_{eff}/dx (and

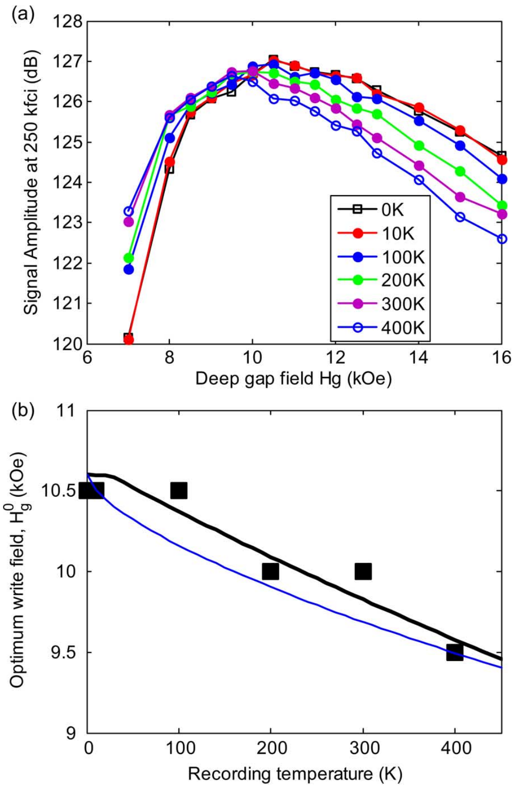

Fig. 2. (a) Signal amplitude at 250 kfci versus writer deep-gap field for different recording temperature. (b) Optimum writer field $\mathrm{H_g^0}$ as a function of the recording temperature. Black line is $\mathrm{H_g^0(T)}$ calculated from Eq. (3) with $\mathrm{R} = 2\mathrm{e}11\ \mathrm{Oe/s}$. Fine blue line is $\mathrm{H_g^0(T)}$ calculated from Eq. (2) with $\mathrm{t_{eff}} = 3\ \mathrm{ns}$.

therefore dH_{eff}/dt) is expected to decrease with the recording temperature. The finite writer rise time is also expected to reduce the effective field rate R but its influence on the variation of $\mathrm{H_g^0}$ with T is difficult to quantify.

Next, for each temperature, recording simulations are performed at different write frequencies using the optimum $\mathrm{H_g^0}$ value derived above. For each temperature, signal spectra at 250 and 500 kfci are obtained. Fig. 3 shows for instance the signal spectra corresponding to recording at 300 K. The signal roll-off allows extracting the effective magnetic spacing $(\mathrm{d + a})$ and, since the medium noise is dominated by particulate noise, a fit of the noise spectrum gives the head-media spacing d [13], [14]. Thereby, we can derive the evolution of the transition parameter, a, as a function of the recording temperature [Fig. 4(a)]. Broadband signal-to-noise-ratios (BB-SNR), defined as the signal power divided by the noise power integrated over 0 to 0.01 $\mathrm{nm^{-1}}$ bandwidth, are also calculated as a function of the recording temperature [Fig. 4(b)].

Thermal activation is found to significantly affect the medium BB-SNR. The BB-SNR at 250 and 500 kfci decrease by 1 to 2 dB, when the recording reaches 400 K compared to a 0 K simulation. This change of BB-SNR is fully explained by a degradation of the written transition quality with T. Fig. 4(b) shows that the transition parameter increases from 14 nm at 0 K to close to 18 nm at 400 K. The variation of the parameter a versus T is fairly linear and can be approximated by

$$a(nm) = 14.2\left[1 + 7.10^{-4}.T(K)\right]. \quad (4)$$

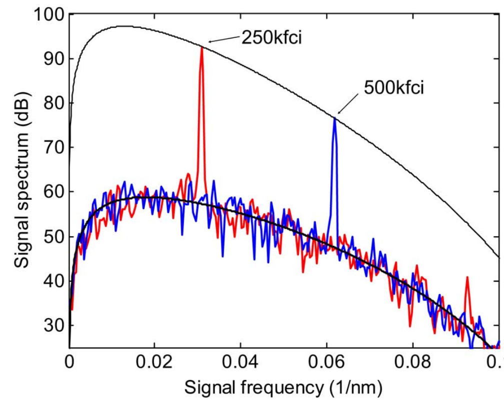

Fig. 3. 250 and 500 kfci signal spectra obtained from simulations performed for a recording temperature $\mathrm{T} = 300\ \mathrm{K}$. Lines are signal roll-off fit $(\mathrm{d + a} = 43\ \mathrm{nm})$ and noise spectrum fit $(\mathrm{d} = 24\ \mathrm{nm})$.

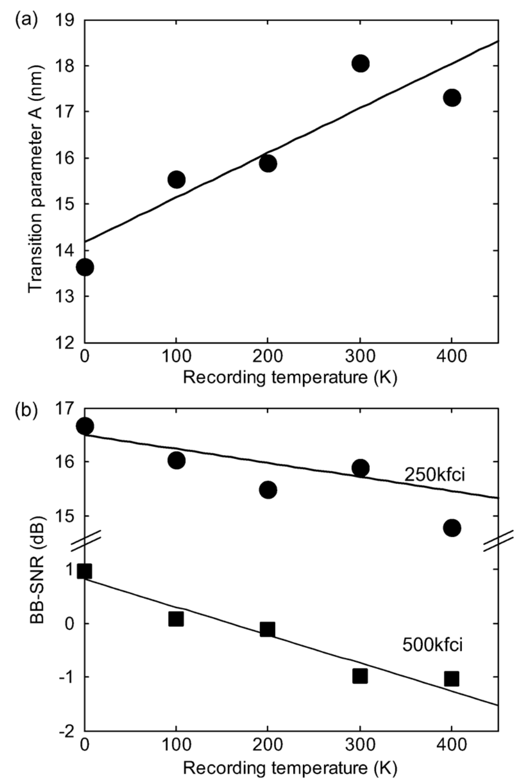

Fig. 4. (a) Variation of the recorded transition parameter versus the recording temperature T. Dots are simulation results and the line is a linear regression. (b) Variation of BB-SNR values versus T. Symbols are simulation results and the lines are predictions of the BB-SNR using, for the transition parameter, the linear approximation of Fig. 4(a).

This approximation is used to calculate the continuous variation of BB-SNR with T and write frequency in Fig. 4(b), by using analytical forms of the signal roll-off [13], [14].

As pointed out already, the evolution of the transition parameter results from the broadening of the switching field distribution, $\sigma_{\mathrm{Hsw}}/\mathrm{H_{sw}}$, with temperature [6]. We wish to relate the variation of $\sigma_{\mathrm{Hsw}}/\mathrm{H_{sw}}$ with the recording temperature. An analytical expression for $\sigma_{\mathrm{Hsw}}/\mathrm{H_{sw}}$ at different sweep rates has been proposed for a perfectly oriented perpendicular medium by Hovorka *et al.* [22]. Similar equation for an imperfectly oriented medium could be derived. Here, we use a numerical approach based on (3) to calculate $\sigma_{\mathrm{Hsw}}/\mathrm{H_{sw}}$ as a function of T with $\sigma_{\mathrm{Hk}}/\mathrm{H_k} = 0.150$ and a constant field rate $\mathrm{R} = 2\mathrm{e}11\ \mathrm{Oe/s}$.

$\sigma_{\mathrm{Hsw}}/\mathrm{H_{sw}}$ is found to increase almost linearly between 0.150 at 0 K and 0.158 at 400 K. Such variation of the switching field distribution does not fully account for the observed increase in transition widths. Assuming a constant field rate R appears to be too crude an approximation to properly evaluate the broadening of the switching field distribution during the write process and thus to quantify *a priori* the variation of transition parameter at nonzero temperature. A more refined model would be needed, which includes the temperature variations of field gradient and the finite writer rise time.

V. Conclusion

The effect of thermal fluctuation on the recording performance of a perpendicularly-oriented barium-ferrite particulate medium was investigated using micromagnetic simulations. The write simulations were performed with a highly-efficient particle micromagnetic solver designed to run on GPU. Large media slabs, containing 23 000 particles, were evaluated, which allowed deriving signal spectra with meaningful statistics. The optimum write field was found to decrease with the recording temperature, which correlates with the reduction of the medium mean switching field due to thermal fluctuations. The medium BB-SNR was also calculated at different recording frequencies and temperatures. A significant BB-SNR loss (several decibels) was obtained at 400 K compared to the 0 K case. The loss of SNR arises from an increase of the written transition width with T. Thermal fluctuations were found to significantly impact the recording performance of the particulate medium and should therefore be properly accounted for when assessing the medium limits. The obtained results are also relevant for understanding the performance of granular media in magnetic recording.

Acknowledgment

This project was supported in part by the fellowship program of "Obra Social la Caixa."

References

[1] D. Berman, R. Biskeborn, N. Bui, E. Childers, R. D. Cideciyan, E. Eleftheriou, D. Hellman, R. Hutchins, W. Imaino, G. Jaquette, J. Jelitto, P.-O. Jubert, C. Lo, G. McClelland, S. Narayan, S. Ölçer, T. Topuria, T. Harasawa, A. Hashimoto, T. Nagata, H. Ohtsu, and S. Saito, "6.7 Gb/in2 recording areal density on barium ferrite tape," *IEEE Trans. Magn.*, vol. 43, no. 8, pp. 3502–3508, Aug. 2007.

[2] P.-O. Jubert and S. Onodera, "Metal evaporated media," in *Handbooks of Magnetic Materials*, K. H. J. Buschow, Ed. New York, NY, USA: Elsevier, 2012, vol. 20, pp. 65–121.

[3] S. Matsunuma, T. Inoue, T. Watanabe, T. Doi, Y. Mashiko, S. Gomi, K. Hirata, and S. Nakagawa, "Playback performance of perpendicular magnetic recording tape media for over-50-TB cartridge by facing targets sputtering method," *J. Magn. Magn. Mat.*, vol. 324, no. 3, pp. 260–263, Feb. 2012.

[4] G. Cherubini, R. D. Cideciyan, L. Dellmann, E. Eleftheriou, W. Haeberle, J. Jelitto, V. Kartik, M. A. Lantz, S. Ölçer, A. Pantazi, H. E. Rothuizen, D. Berman, W. Imaino, P.-O. Jubert, G. McClelland, P. V. Koeppe, K. Tsuruta, T. Harasawa, Y. Murata, A. Musha, H. Noguchi, H. Ohtsu, O. Shimizu, and R. Suzuki, "29.5-Gb/in2 recording areal density on barium ferrite tape," *IEEE Trans. Magn.*, vol. 47, no. 1, pp. 137–147, Jan. 2011.

[5] A. Matsumoto, Y. Murata, A. Musha, S. Matsubaguchi, and O. Shimizu, "High recording density tape using fine barium-ferrite particles with improved thermal stability," *IEEE Trans. Magn.*, vol. 46, no. 5, pp. 1208–1211, May 2010.

[6] X. Z. Cheng and M. B. A. Jalil, "The effect of thermal fluctuation on tilted perpendicular media," *J. Appl. Phys.*, vol. 97, no. 10, p. 10E314, May 2005.

[7] S. Batra, W. Scholz, and T. Roscamp, "Effect of thermal fluctuation field on the noise performance of a perpendicular recording systems," *J. Appl. Phys.*, vol. 99, no. 8, p. 08E706, Apr. 2006.

[8] H. J. Richter, A. Lyberatos, U. Nowak, R. F. L. Evans, and R. W. Chantrell, "The thermodynamic limits of magnetic recording," *J. Appl. Phys.*, vol. 111, no. 3, p. 033909, Feb. 2012.

[9] B. Livshitz *et al.*, "Nonuniform grid algorithm for fast calculation of magnetostatic interactions in micromagnetics," *J. Appl. Phys.*, vol. 105, no. 7, p. 07D541, Apr. 2009.

[10] S. Li, B. Livshitz, and V. Lomakin, "Fast evaluation of Helmholtz potential on graphics processing units (GPUs)," *J. Comp. Phys.*, vol. 229, no. 22, pp. 8463–8483, Nov. 2010.

[11] E. Bleszynski, M. Bleszynski, and T. Jaroszewicz, "AIM: Adaptive integral method for solving large-scale electromagnetic scattering and radiation problems," *Radio Sci.*, vol. 31, no. 5, pp. 1225–1251, Sep./Oct. 1996.

[12] B. Biskeborn and P.-O. Jubert, "Bulletpack: A fast, flexible packing algorithm for particulate media," *IEEE Trans. Magn.*, vol. 46, no. 3, pp. 880–885, Mar. 2010.

[13] P.-O. Jubert and G. Alighieri, "Micromagnetic modeling of particulate tape media with increasing perpendicular orientation," *J. Appl. Phys.*, vol. 111, no. 7, p. 07D124, Apr. 2012.

[14] P.-O. Jubert, B. Biskeborn, D. Qiu, A. Matsumoto, H. Noguchi, and O. Shimizu, "Noise and recording properties of barium-ferrite particulate media studied by micromagnetic modeling," *IEEE Trans. Magn.*, vol. 47, no. 2, pp. 386–394, Feb. 2011.

[15] T. J. Szczech and P. Iverson, "Improvement of the coefficients in field equations for thin-film recording heads," *IEEE Trans. Magn.*, vol. MAG-23, pp. 3866–3867, Sep. 1987.

[16] R. I. Potter, "Digital magnetic recording theory," *IEEE Trans. Magn.*, vol. MAG-10, no. 3, pp. 502–508, Apr. 1974.

[17] M. P. Scharrock, "Time-dependent magnetic phenomena and particle-size effects in recording media," *IEEE Trans. Magn.*, vol. 26, no. 1, pp. 193–197, Jan. 1990.

[18] M. P. Scharrock, "Measurement and interpretation of magnetic time effects in recording media," *IEEE Trans. Magn.*, vol. 35, no. 6, pp. 4414–4422, Nov. 1999.

[19] R. W. Chantrell, G. N. Coverdale, and K. O'Grady, "Time dependence and rate dependence of the coercivity of particulate recording media," *J. Phys. D: Appl. Phys.*, vol. 21, pp. 1469–1471, 1988.

[20] X. Feng and P. B. Visscher, "Sweep-rate-dependent coercivity simulation of FePt particle arrays," *J. Appl. Phys.*, vol. 95, pp. 7043–7045, 2004.

[21] Q. Peng and H. J. Richter, "Field sweep rate dependence of media dynamic coercivity," *IEEE Trans. Magn.*, vol. 40, no. 4, pp. 2446–2448, Jul. 2004.

[22] O. Hovorka, R. F. L. Evans, R. W. Chantrell, and A. Berger, "Rate-dependence of the switching field distribution in nanoscale granular magnetic materials," *Appl. Phys. Lett.*, vol. 97, p. 062504, 2010.