Effect of thermal fluctuation field on the noise performance of a perpendicular recording system

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We have studied the effect of thermal fluctuations on the transition jitter of a perpendicular recording system using a micromagnetic recording model. A stochastic thermal field term is added to the total effective field in the Landau-Lifshitz-Gilbert equation of motion to simulate thermal fluctuations. The recording model uses a head field generated by a finite element model in the presence of a soft underlayer. A Monte Carlo simulation of 300 isolated transitions is done to calculate the variation in transition jitter. Transition jitter is significantly increased in the presence of a stochastic thermal field for different media parameters. Our results highlight that the thermal fluctuation fields must be included in a realistic assessment of the system performance. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2165599]

I. INTRODUCTION

It is believed by many in the storage industry that conventional perpendicular magnetic recording[1,2] will be able to extend the areal density up to 1000 Gb/in^2. The recording industry has relied on scaling down the grain size to reduce media noise while simultaneously increasing the anisotropy field H_K and the coercivity of the media for thermal stability. As grain volume decreases, the stochastic thermal fluctuation field increases the probability for magnetization to switch its orientation.[3] The thermally assisted switching gives rise to the time dependence of magnetization decay.[4,5] Given that hard disk drives are not operated at 0 K, a question is raised on the effect of thermal fluctuations on the quality of written transition at drive operating temperatures. The effect of thermal fluctuations can degrade the transition as it is written and will lead to a low signal-to-noise ratio (SNR) for the recording system. Media damping plays a critical role in the write process as it defines how quickly magnetization settles into its final state. In this paper, we have explored the effects of thermal fluctuations and media damping on the quality of written transitions.

II. MODEL

A finite element model[6] (FEM) is used to generate head fields in the presence of a soft underlayer (SUL). In this model, the SUL is treated as a nonlinear, magnetic permeable material with an initial relative permeability value of 500. The write field profiles obtained by the FEM are used in a micromagnetic media model[7] to simulate the recording process. We have also used a large-scale micromagnetic model[8,9] to model the write head and the SUL to compute the write field. The dynamic write process uses the Landau-Lifshitz-Gilbert (LLG) equation of motion to calculate the temporal evolution of the magnetization vector of each grain within the medium. The effect of the thermal fluctuation field is included in micromagnetic simulations by adding a stochastic thermal field to the local magnetic field.[3] After adding the thermal field, we get the stochastic LLG equation with $\mathbf{H}_{\rm loc}$ shown below,

$$\frac{d\mathbf{m}}{dt} = \frac{-\gamma}{1+\alpha^2}\mathbf{m}\times[\mathbf{H}_{\rm loc}+\alpha\mathbf{m}\times\mathbf{H}_{\rm loc}].$$

where $\mathbf{H}_{\rm loc}=\mathbf{H}_K+\mathbf{H}_{\rm demagnetization}+\mathbf{H}_{\rm exchange}+\mathbf{H}_{\rm applied}+\mathbf{H}_{\rm thermal}$. The thermal field is modeled as a Gaussian stochastic process with the following statistical properties:

$$\langle\mathbf{H}_{{\rm th},i}(t)\rangle=0,\quad \langle\mathbf{H}_{{\rm th},i}(t)\mathbf{H}_{{\rm th},j}(t')\rangle = 2\frac{\alpha k_B T}{\gamma V M_s}\delta_{ij}\delta(t-t').$$

The medium has a pseudo-Voronoi grain structure, which is based on a simulated grain growth process using a regularly spaced (1.5 nm) lattice of square subgrains. This naturally leads to a log-normal grain-size distribution. The medium also includes a log-normal distribution of the crystalline anisotropy field magnitude and a Gaussian distribution for its orientation. Demagnetizing fields are calculated by Fourier transforms over the underlying uniform grid. Written patterns are calculated by integrating the Landau-Lifshitz-Gilbert equation as the head passes over the media. The written transition pattern is read back using a read sensitivity function in conjunction with a reciprocity-based read process.[7] The read process does not include any time-dependent degradation of written transition. A Monte Carlo simulation of 300 isolated transitions is done to calculate the transition jitter as the variation in the zero-crossing position of the read-back voltage of each transition. The transition parameter is calculated by an hyperbolic tangent fit to the isolated transition. We use a bootstrap method[10] to calculate the lower and upper bounds of the transition jitter and transition parameter at 95% confidence level.

III. RESULTS AND DISCUSSION

Several cases of heads and media parameters were modeled with and without the thermal fluctuation field. These are shown as cases 1–12 in Table I. First we discuss the results

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TABLE I. Simulation parameters and results.

Case	*HK* (kOe)	Stochastic thermal field	α	h_e	Jitter	+/−95% confidence	*a* parameter	+/−95% confidence
1	15	off	0.10	0.09	1.63	0.13	4.67	0.14
2	15	on	0.10	0.09	2.16	0.19	4.91	0.19
3	17	off	0.10	0.07	1.06	0.08	3.29	0.09
4	17	on	0.10	0.07	1.37	0.12	3.70	0.11
5	15	off	0.05	0.09	2.02	0.15	4.96	0.16
6	15	off	0.10	0.09	1.63	0.13	4.67	0.14
7	15	off	0.20	0.09	1.31	0.10	4.21	0.12
8	15	off	0.40	0.09	1.14	0.09	4.02	0.11
9	15	on	0.05	0.09	2.44	0.19	5.19	0.21
10	15	on	0.10	0.09	2.16	0.19	4.91	0.19
11	15	on	0.20	0.09	1.78	0.12	4.62	0.16
12	15	on	0.40	0.09	1.76	0.13	4.43	0.15

for a head design presented previously.[11] The head 1 design includes a down-track shield (DS). The modeled head has a physical track width of 40 nm, a relatively thick pole (320 nm), a short throat length (20 nm), and a head-to-media spacing (HMS) of 5 nm to maximize the write field. The maximum effective field (H_{eff}) for this head at a distance of 10 nm from the pole is calculated to be 1.87 T. The relevant media parameters are $4\pi M_s$ of 579 emu/cm^3, thickness of 12 nm, and grain size of 5.7 nm. Anisotropy field H_K, damping constant (α), and intergranular exchange h_e for two different media are listed in Table I. In addition, a log-normal grain size with volume distribution of 30%, a log-normal distribution in the crystalline anisotropy field of 5% in magnitude, and a Gaussian distribution for its orientation of 3.5° are assumed. Figure 1 shows the results of a Monte Carlo simulation for an isolated transition. A significant transition curvature is observed, and a jitter value of 1.63 nm is obtained for case 1. When a thermal field corresponding to a temperature of 293 K is turned on, we see an increase in the width of the written transition. This effect is understood by realizing that the coercivity of the media is lowered at higher temperatures, leading to a larger write bubble. The larger write bubble leads not only to a wider write width but also to an increase in the transition parameter (a parameter) from 4.67 to 4.91 nm and a shift in the transition location from 5.78 to 9.43 nm. In addition, the transition gets noisier, as confirmed by the transition jitter value of 2.16 nm (case 2). This effect is shown in Fig. 2. Next, we have used a different head configuration that gives a larger head field (H_{eff} of 2.2 T at a distance of 10 nm from the pole) and a higher field gradient and is able to write on the higher H_K media. Again, we see an increase in *a* parameter from 3.29 to 3.70 nm, with a corresponding increase in jitter from 1.06 to 1.37 nm (cases 3 and 4) and a shift in the transition location from 3.86 to 5.42 nm as stochastic thermal fluctuation fields are turned on.

We use the system criterion that jitter is less than 10% of the bit cell as an estimate of linear density. Based on this criterion, the linear density will degrade from 1558 kbpi (case 1) to 1176 kbpi (case 2) for head 1, i.e., a decrease of 24% in the presence of thermal field. The results for the head 2 that is capable of producing larger field and a larger field gradient at the media show that linear density will degrade from 2405 kbpi (case 3) to 1854 kbpi (case 4), i.e., a degradation of 23% in the presence of thermal fluctuation field. The increase in jitter value includes all aspects of writing and is a complex function of write field, write field gradient, and media parameters such as H_K, grain size, $4\pi M_s$, and exchange parameter h_e. We attribute the increase in the jitter values to the fact that the thermal fluctuation field is small yet significant in comparison to the total effective field without the thermal fluctuation field term.

Next, we have modeled media with different damping values "α" ranging from 0.05 to 0.4 corresponding to cases 5, 6, 7, and 8 using head 1. As the damping value is in-

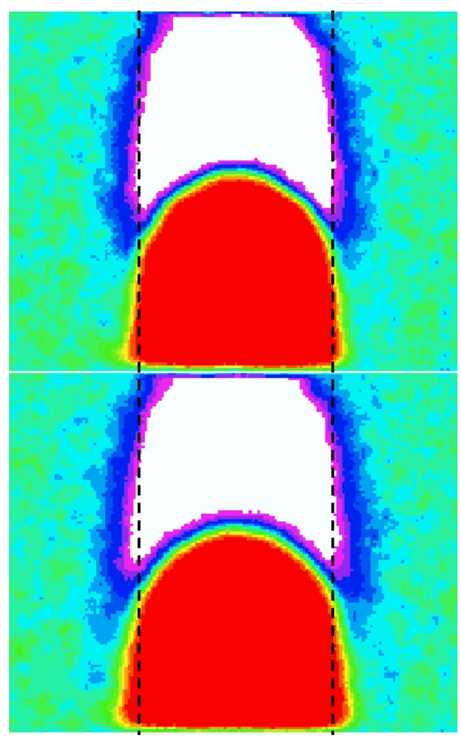

FIG. 1. Monte Carlo simulation results using micromagnetic write model for an isolated transition showing an increase in write width. The upper panel is without thermal fluctuation field and the lower panel includes thermal fluctuation field.

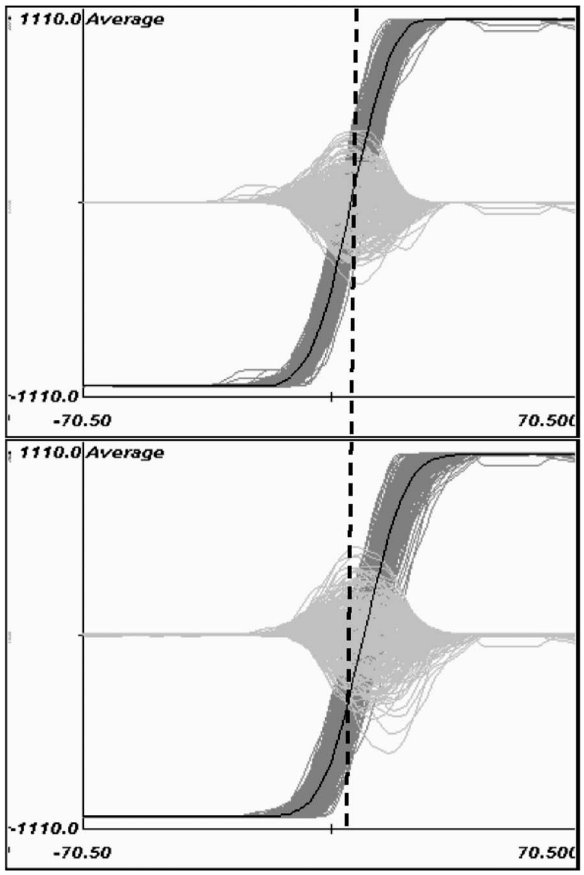

FIG. 2. Wave forms and associated noise for cases 1 and 2 based on a Monte Carlo simulation for 300 isolated transitions as thermal fluctuation fields (lower panel) are included.

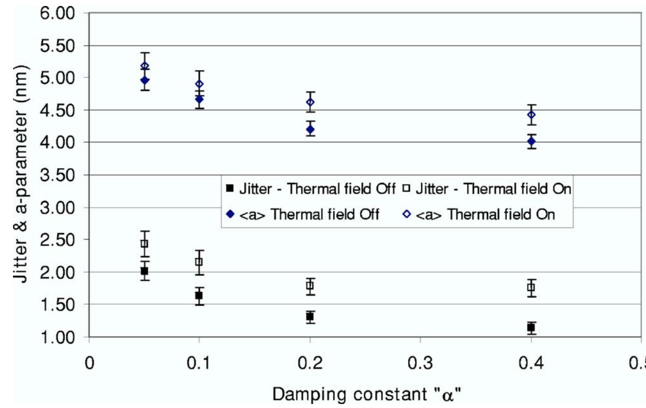

FIG. 3. Transition jitter and a parameter with and without thermal fluctuation field as functions of damping value α.

creased from 0.05 to 0.4, we observe a decrease in the jitter value and a decrease in the a parameter. These values with associated 95% confidence level (average of +/−95%) are listed in Table I. This is expected as an increasing damping value reduces the time it takes for magnetization to settle into its final state. However, there is an optimal value of damping for the recording system when flux rise-time considerations are included.[12] As the thermal fluctuation field term is included in the model, we see a similar decrease in the absolute value of jitter and a parameter (cases 9–12). The results for the two cases for the transition jitter and the a parameter as functions of damping α are plotted in Fig. 3. Our results show that the percentage increase in the jitter value or jitter ratio (thermal field on/thermal field off) increases as a function of damping value α.

IV. CONCLUSIONS

We have considered the effect of the thermal fluctuation field corresponding to a temperature of 293 K in micromagnetic simulations of a perpendicular recording system. At higher temperatures, the size of the write bubble increases due to a reduction of the media coercivity. This leads to an increase in the transition width and a shift in the transition location. The inclusion of the thermal fluctuation field increases the probability of magnetization switching, that coupled with a larger write bubble, leads to a larger transition jitter. Using a system criterion that transition jitter is less than 10% of the bit cell, we find that the inclusion of the thermal fluctuation field degrades the linear density by approximately 24% for the two cases studied. Therefore, we conclude that including thermal fluctuation field degrades the system performance. We have studied this effect as a function of damping value of the media. With increasing damping value, the absolute values of the jitter decrease, confirming that a sharper transition is written as media settle quickly into its final state. The inclusion of thermal fluctuation increases the probability of magnetization reversal of individual grains. Consequently, when thermal fluctuation fields are included, there is an increase in jitter value for all damping values α compared to the case when thermal fluctuation field is not included. Our results show that the percentage increase in the jitter values in the presence of thermal fluctuation field increases for increasing damping values of the media. The fact that operating temperature requirements for the hard disk drives are between 300 and 350 K, the effect of thermal fluctuation fields and media damping needs to be included to optimize a recording system for high areal density.

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