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Transition Characterization for Perpendicular Heat-Assisted Magnetic Recording System

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Abstract

In order to promote the extremely high areal density of perpendicular magnetic recording system that is approaching its super-paramagnetic limit, the future technology known as heat-assisted magnetic recording (HAMR) has been proposed because perpendicular recording has many advantages over longitudinal recording, including high write field amplitude, sharp field gradient, well-aligned medium, less demagnetization field at transition, and so on. Thus the HAMR system is currently developed as extension of this perpendicular magnetic recording scheme. In this paper, we study the transition characteristics of perpendicular HAMR systems by varying some concerned parameters (e.g., peak temperature, write head gap, deep gap field, etc.) to optimize the performance of the HAMR system. Results show that the write head gap and the deep gap field are crucial parameters that are needed to be minimized so as to achieve high performance. In addition, we use each transition center in the simulation result to calculate nonlinear transition shift (NLTS) value to observe the dependence of NLTS on the distance between transitions and the relationship between write head gap. The results lead to the observation that the wide write head gap will increase the NLTS in the system, which degrade the overall system performance.

Keywords: HAMR, Super-paramagnetic limit, NLTS

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1. Introduction

At present, the magnetic recording technology used in hard disk drives (HDDs) is completing a transition from the use of longitudinal to perpendicular magnetic orientation of the medium. This terminology refers to the way the tiny magnet particles or grains are aligned in the recording process. Longitudinal recording means that the recorded magnets align along the circumferential tracks on a disk since their commercial deployment more than fifty years ago. Because of an energetic advantage for the perpendicular configuration when packing the regions of opposite magnetic polarity close to each other, i.e., high areal density (AD), and a worthwhile advantage in write-ability and SNR potential, this gives a performance edge to perpendicular recording. It is the threat of degrading thermal stability in the longitudinal recording that explains this.

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Perpendicular recording solves this situation (at least in a short term) with perhaps the least pervasive modification of the longitudinal recording system. However, a weakness of the perpendicular approach is that its AD improvement potential relative to the best commercial longitudinal HDD systems is generally thought to lie in 3 – 4 times range, not a huge gain given the increased complexity of the system change. It is perhaps only the drastic slow-down in the AD compound annual growth rate since the year that makes this modest extension tolerable. The problem is that to store data reliably using a very small bit size, the magnetic medium must be made of a material with a very high coercivity. At some capacity point, the bit size is so small and the coercivity is so high that the magnetic field used for writing data cannot be made strong enough to permanently affect the data, thus the data can no longer be written into the disk (known as super-paramagnetic limit).

HAMR is certainly one of a few candidates that can solve this problem by temporarily and locally changing the coercivity of the magnetic medium by raising the temperature above the Curie temperature using a laser, so that a realistically achievable magnetic write field can write data into a medium. Although the characterization of perpendicular HAMR have previously been studied in [1, 2], these studies do not investigate how the system response behaves when given parameters (e.g., write head gap, medium coercivity, fly height) vary. In addition, Kaewpukdee *et al*. [3] studied the transition characteristics of longitudinal HAMR systems and found that the fly height has the most impact on the transition parameter and the PW_{50}, followed by the peak temperature.

The rest of this paper is structured as follows. Sections 2 and 3 briefly explain the perpendicular HAMR system and its microtrack model, respectively. Section 4 describes the simulation settings and results. Finally, conclusion is given in Section 5.

2. Perpendicular HAMR

In perpendicular magnetic recording system, the magnetic field from the writer head magnetizes the medium in vertical direction. Fig. 1(a) shows the actual configuration of the system that consists of the writer head, medium, and magnetic field. The special layer in the medium called soft magnetic underlayer (SUL) or “keeper” is employed to help a magnetic field travel back from the main pole to the return pole of a writer core. It contributes the direction of magnetization in the medium to be perpendicular to the medium. The magnetic field derived by Westmijze [4] is given as a complex function that can be solved using a numerical method.

Due to the head and medium equivalent simulation in Fig. 1(b), we are able to get the magnetic field of a writer. However, the pole image of a writer is to be symmetrically placed near a horizontal axis. When rotating it 90 degree in counterclockwise direction, its magnetic field will look like that obtained from a longitudinal system. This means that we can still utilize a Karlqvist concept [5] to estimate the magnetic field of a writer in perpendicular system, which is given by.

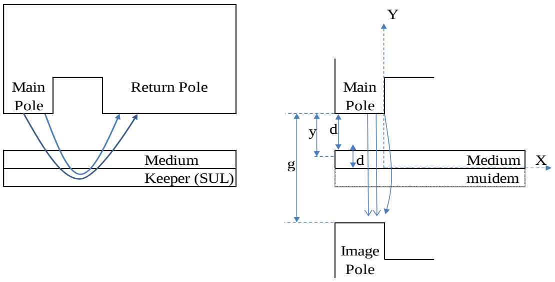

Fig. 1. Perpendicular recording system for (a) actual configuration ; (b) an equivalent configuration

$$H_h = H_y(x,y) = \frac{H_0}{\pi}\left[\tan^{-1}\left[\frac{y+g/2}{x}\right] - \tan^{-1}\left[\frac{y-g/2}{x}\right]\right] \tag{1}$$

where g is a spacing width between a pole head and a pole image, H_0 is the magnetic field of a writer within a gap (or gap field). If δ is a medium thickness and d is a flying height, we obtain $g = 2d + 2\delta$. Similarly, in the Thermal William-Comstock model, the magnetic field is considered merely at the center of a medium thickness ($y = d + \delta/2$) as illustrated in Fig. 1(b), and no need to consider magnetic field in parallel direction with medium $H_x(x,y)$.

Practically, the estimated magnetic field from (1) will be valid only when $x > 0$ because the transition location occurs slightly far away from the edge of a writer pole. Then, we can also use (1) together with a Thermal William Comstock model to analyze a longitudinal HAMR system. We can obtain the magnetic field gradient at the center of magnetic transition $x = x_0$ by taking a derivative of (1) with respect to x, i.e.,

$$\left.\frac{dH_x(x)}{dx}\right|_{x_0} = \frac{H_0}{\pi}\left[\frac{A}{x^2 + A^2} - \frac{B}{x^2 + B^2}\right] \tag{2}$$

where $A = y - g/2$ and $B = y + g/2$. For the demagnetization field calculation, we can obtain from [6]

$$H_d(x) = -\frac{dM(x)}{dx} * H_y^{step}(x) \tag{3}$$

When the field from a sharp transition at the center of medium is given by [7]

$$H_y^{step}(x) = \frac{1}{\pi}\tan^{-1}\left(\frac{2x}{\delta}\right) \tag{4}$$

If the magnetization status is the arctangent function, by substituting (4) and longitudinal magnetization gradient [8] equation into eqn.(3). The demagnetization field can be calculated as

$$H_d(x) = -\frac{2}{\pi^2}\int_{-\infty}^{+\infty}\tan^{-1}\left(\frac{z - x_0}{a}\right)\frac{dM(T)}{dT}\frac{dT(z)}{dz}\tan^{-1}\left(\frac{2(x-z)}{\delta}\right)dz - \frac{2}{\pi^2}\int_{-\infty}^{+\infty}\frac{M_\gamma(z)a}{a^2 + (z - x_0)^2}\tan^{-1}\left(\frac{2(x-z)}{\delta}\right)dz \tag{5}$$

For the perpendicular HAMR system that has a big size of heating spot, the first term of (4) can be ignored. Thus, the demagnetization field reduce to

$$H_d(x) \approx -\frac{2M_\gamma(T(x))}{\pi}\tan^{-1}\left(\frac{x - x_0}{a + \delta/2}\right) \tag{6}$$

If the heating gradient of remanent magnetization is not considered, the demagnetization gradient at any x along the track is

$$\frac{dH_d(x)}{dx} \approx -\frac{2M_\gamma(T(x))}{\pi}\left\{\frac{(a + \delta/2)}{(a + \delta/2)^2 + (x - x_0)^2}\right\} \tag{7}$$

At $x = x_0$, we obtain

$$\left.\frac{dH_d(x)}{dx}\right|_{x_0} \approx -\frac{2M_\gamma(T(x_0))}{\pi(a + \delta/2)} \tag{8}$$

Furthermore, similar to the derivation for longitudinal recording in [8], we get the analytic expression for the transition parameter in perpendicular recording according to

$$a = -\frac{\gamma}{2} + \frac{1}{2}\sqrt{\gamma^2 + \left.\frac{4H_c(1 - S^*)\delta}{\Delta\pi}\right|_{x_0}} \tag{9}$$

where,

$$\Delta = \frac{dH_h}{dx} - \frac{dH_c}{dT}\frac{dT}{dx}\bigg|_{x_0} = \frac{H_0 g}{\pi\left(x_0^2 + \left(\frac{g}{2}\right)^2\right)} - \frac{dH_c}{dT}\frac{dT}{dx}\bigg|_{x_0}$$

$$\gamma = \frac{2M_\gamma}{\Delta\pi} - \frac{\delta}{2} + \frac{2H_c\left(1 - S^*\right)}{\Delta\pi}$$

3. Microtrack Model

In this section, we describe the microtrack model that captures the two dimension processes of HAMR (i.e., heating process and medium magnetization process). In general, the approximately Gaussian distribution of temperature profile in the system that impacts the transition characteristic variation on both across and along tracks, while the Thermal William-Comstock model provides only a one dimensional solution (not consider the impact on cross-track variation) to determine the transition characteristic problem.

Consequently, to estimate the transition curvature correctly, the magnetic track must be divided into N sub-tracks with Δz equal width as displayed in Fig. 2, where $T(x,z)$ is the temperature profile that occurs from medium heating, x is an along-track direction and y is an across-track direction. Thus the temperature profile in each sub-track is approximated to be one dimensional function $T(x, z = i\Delta z)$ for $-N/2 \leq i \leq N/2$. Note that the more the number of sub-tracks, the better the approximation. As a result, by applying the Thermal William Comstock model to each sub-track, we can determine the transition parameter and the transition center of each sub-track. If the transition response in each sub-track is equal to $h(a_i, t - \tau_i)$, the total transition response of all sub-tracks is given by [9]

$$p(t) = \frac{1}{N}\sum_{i=1}^{N} h\left(a_i, t - \tau_i\right) \qquad (10)$$

where τ_i and a_i are the transition center and the transition parameter of each sub-track, respectively.

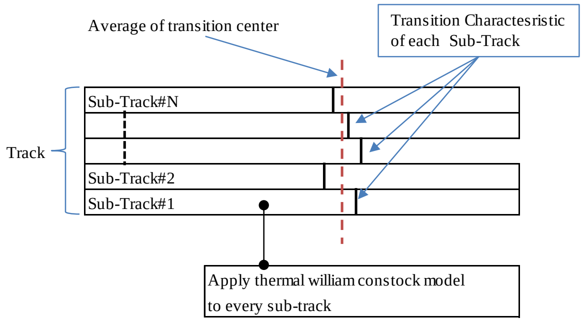

Fig. 2. A Microtrack model of HAMR channel

4. Simulation Result

To investigate the transition characteristics of a perpendicular HAMR system, the setup parameters used to analyze the system response are given in Table 1.

Table 1. Simulation parameters

Parameters	Setting Value
Peak Temperature (T_{peak})	400° C
Sigma of peak temperature (σ_t)	70
Down track location of Peak Temperature (c)	0 nm
Deep gap field (H_g)	1.9×10^6 A/m
Write head gap (g)	80 nm
Fly Height (d)	19 nm
Width of the gap (wt)	180 nm
Number of sub-track (N)	14
Coercive squareness (S^*)	0.7
Remanant Magnetization(M_r)	$-1200\ T(x) + 12 \times 10^5$ A/m
Coercivity (H_c)	$-2000\ T(x) + 21 \times 10^5$ A/m

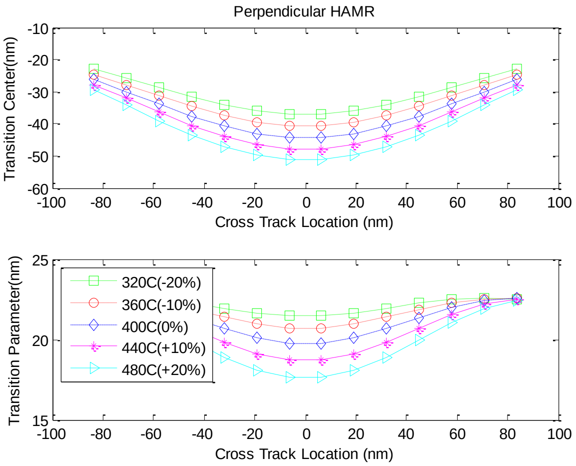

Fig. 3. Effect of peak temperature on the transition center and transition parameter of perpendicular HAMR system

Figure 3 shows the effect of peak temperature on the transition center and transition parameter of a perpendicular HAMR system, where the peak temperature varies between 400°C ±20%. The transition center places away from the gap center of the head when increasing the peak temperature, whereas the transition parameter is decreased (highly preferable). Hence, we need to trade-off both of them when choosing the peak temperature used in perpendicular HAMR system. Table 2 summarizes the average of transition center and transition parameter when varying some concerned parameters from the default setting by ±20%. From this table, the effect of write head gap and deep gap field reduction could reduce the transition parameter, PW_{50} and transition center to close nearby the gap center of the head. Figures 4 and 5 illustrate the graphical summary characteristics of these parameters in details.

Table 2. The average of transition center and transition parameter when varying some parameters from the default setting by ±20%

PARAMETER	Average	% variation of each parameters				
		-20 %	-10 %	0 %	+10 %	+20 %
Peak Temperature (T_{peak})	X_0 (nm)	-30.93	-33.69	-36.48	-39.27	-42.03
	a (nm)	22.13	21.75	21.26	20.67	19.997
	PW_{50} (nm)	84	84	83	83	82
Coercivity (H_c)	X_0 (nm)	-25.48	-30.79	-36.48	-42.48	-48.7
	a (nm)	18.46	19.86	21.26	22.6	23.85
	PW_{50} (nm)	77	80	83	87	90
Write Head gap (g)	X_0 (nm)	-29.26	-33.02	-36.48	-39.72	-42.76
	a (nm)	17.4	19.35	21.26	23.12	24.93
	PW_{50} (nm)	75	80	83	87	90
Deep gap Field (H_0)	X_0 (nm)	-25.91	-31.41	-36.48	-41.21	-45.65
	a (nm)	15.71	18.47	21.26	24.03	26.76
	PW_{50} (nm)	74	79	83	89	94
Fly Height (d)	X_0 (nm)	-36.48	-36.48	-36.48	-36.48	-36.48
	a (nm)	21.26	21.26	21.26	21.26	21.26
	PW_{50} (nm)	76	91	83	87	91

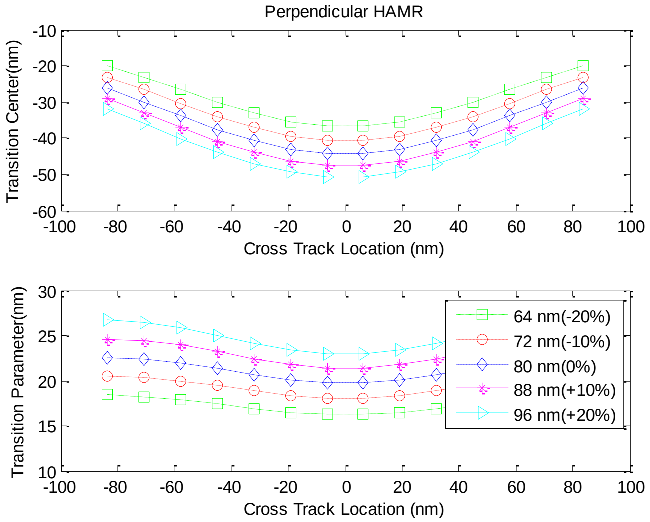

Fig 4. Effect of write head gap (g) on the transition center and transition parameter of perpendicular HAMR system

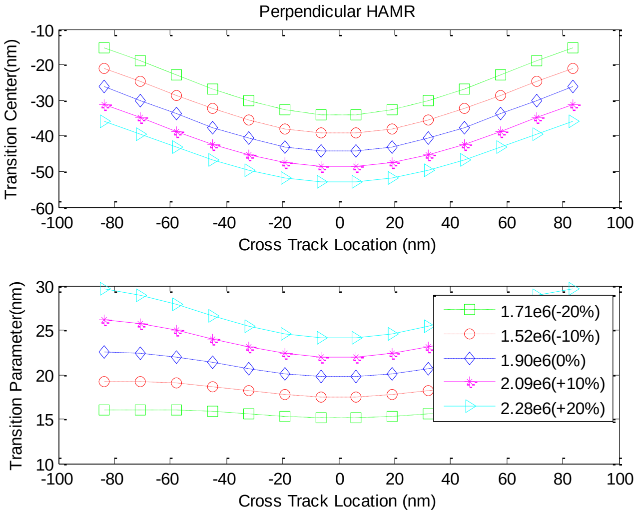

Fig 5. Effect of deep gap field (Hg) on the transition center and transition parameter of perpendicular HAMR system

Effect of Nonlinear Transition Shift

During the write process of magnetic recording, the location of the written bits can be shifted due to interaction between the head field and the demagnetization field of adjacent bits in the previously written transition. This data dependent nonlinear shift is called nonlinear transition shift (NLTS), and creates unwanted distortion in the readback signal. Practically, NLTS degrades the magnetic recording system performance. From [6], the analytical expression of NLTS could be estimated with.

$$H_d(x_0-\Delta)+H_h(x_0-\Delta)=H_c \qquad (11)$$

where x_0 is the location of ideal transition (without NLTS), Δ is an amount of NLTS. Assuming the value of NLTS is small, we can use the Taylor series expansion around x_0 and obtain that the value of Δ is proportional to the value of the demagnetizing field:

$$\Delta=+\frac{H_d(x_0)}{\left(\frac{dH_h}{d_x}\Big|x=x_0\right)} \qquad (12)$$

The NLTS is smaller if the transition parameter and head-medium spacing are smaller and bit length is larger. A medium with a small magnetic moment and a high coercivity will have a small value of NLTS. It has been experimentally observed that the dependence of NLTS on the distance between transitions, which is usually described by some power of distance, i.e.,

$$\Delta\approx K/B^{\gamma} \qquad (13)$$

where the power γ is an experimental measure, typically in the range of 1.5 – 3 and B is the distance between two transitions. We use the transition center obtained from Table 2 when varies the write head gap to calculate an NLTS value for studying their relationship. Table 3 shows the NLTS value in each transition distance (for example, the distance between two transition centers, i.e., x_0 at 0% and x_0 at 10%) with $\gamma = 3$. Results show that the Δ (or an NLTS value) is increased in proportional to the write head gap and the transition center. Their values are kept within 20 – 50% of the distance between transitions to be pre-compensated effectively. This result will help us design the write pre-compensation block that is available in the conventional read channel chips so as to cancel this effect.

Table 3. NLTS value in each distance between two transitions from the transition center obtained from Table 2.

X_0	B	Δ (NLTS)
-29.26	3.76	0.75
-33.02	3.46	0.97
-36.48	3.24	1.18
-39.72	3.04	1.42
-42.76	-	-

5. Conclusion

We introduce the thermal William Comstock and the microtrack model to observe the transition characteristics of perpendicular HAMR systems by varying some concerned parameters. Reducing the write head gap and the deep gap field from the default values will possibly increase an areal density because of a smaller PW_{50}. Additionally, the chosen peak temperature for an HAMR system needs to trade off between the transition center and the transition parameter since they are inversely proportional to the peak temperature. From simulation results, we also use the obtained transition center to study the effects of nonlinearity distortion on the readback signal when two transitions are written close enough. Thus, we observe that the wide write head gap will increase the NLTS, which in turn degrades the overall system performance.

Acknowledgements

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