Optimal Write Head Design for Perpendicular Magnetic Recording

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In this paper, we study the effect of the write head field on the Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER) of a magnetic recording channel, and optimize the write head for perpendicular magnetic recording. Six parameters of the write head for Perpendicular Magnetic Recording (PMR) are studied in the design. An optimal solution of the write head is obtained using design of experiment methodology, the optimum writer field is verified, and the improved recording performances are achieved with the optimally designed write head.

***Index Terms*—Micromagnetics, Magnetics Heads, Design of Experiments, Optimization, Signal to Noise Ratio, Bit Error Rate.**

I. INTRODUCTION

Perpendicular Magnetic Recording (PMR) [1] is widely commercialized but the areal density gains for PMR has been slowing down in recent years. The writer is a very important component of the magnetic recording system with many parameters that need to be optimized. The recording performance depends on many parameters and there are many metrics that could be used to predict the performance, in particular, the write field strength and the write field gradient are two important such metrics. However, the understanding how these intermediate metrics exactly translate into areal density gain is a complex process, which is involving the improvement to the SNR and the BER.

Therefore, we adopt an approach to search for the optimal solution of the write head design based on the maximization of the Signal-to-Noise Ratio (SNR) and the minimization of the Bit Error Rate (BER) via micromagnetic simulations, the grain-flipping probability (GFP) model [2] and channel simulations. We select six variables as the design parameters in the write head of a PMR system. An initial screen testing is performed to decide the nominal values of these parameters and their variations. The design of experiments (DOE) is conducted by applying an orthogonal array (OA) [3][4] and Landau-Lifshitz-Gilbert (LLG) based micromagnetic simulations [4] are carried out to obtain the magnetization distributions in the recording media for each head design. These magnetization distributions are then used to train the corresponding GFP model. The SNRs and BERs are obtained from processing the GFP model output with a software channel. The Taguchi method [3] is used to identify the optimal solution that maximizes the SNRs and minimizes the BERs. Using the Taguchi method, we predict the SNR and the BER at the optimal head design and finally, the verification is performed by micromagnetic simulation, training the GFP model, SNR characterization and BER calculation for the optimal design. A comparison between the optimal write head and one commercial write head is performed.

II. CONCEPTS AND APPROACH

As evaluation of the recording performance of PMR using the electromagnetic and micromagnetic models invariably takes considerable computer resources and time, the major challenge encountered in optimal head design is that we can only perform a limited number of design trials before reaching the optimal. The concept of the Taguchi method, which is proven to be effective, is employed in this study for simulation-based optimal write head design. The procedure of the proposed method involves 10 tasks, which are shown in Fig. 1.

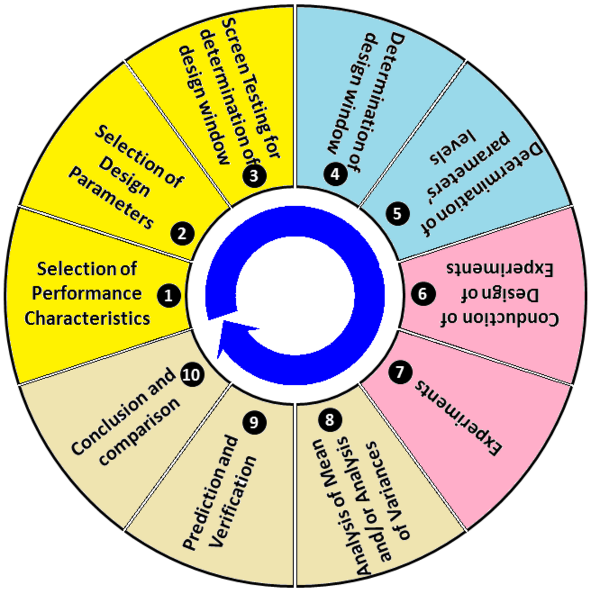

Fig. 1. Stages of optimal write head design.

III. PROCESS AND ANALYSIS

Selection of Performance Characteristics, Design Parameters, and Screen testing for determination of the design window of parameters

The objective of this study is to optimize the write head design to achieve better SNR and lower BER in the PMR system.

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Fig. 2 shows six variables that are chosen as the design parameters; they are the trailing-shield gap (TSG), side-shield gap (SSG), main pole throat height (MPTH), leading shield flare angle (LSFA), main pole taper angle (MPTA) and main pole flare angle (MPFA).

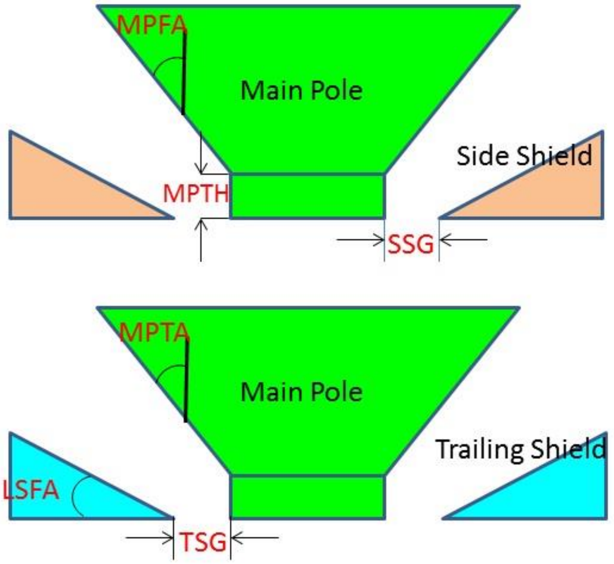

Fig. 2. Outline of the PMR write head, with labeling of design parameters.

A screen testing is performed to determine the nominal values and variation ranges for each parameter according to the modeled head field, the initial micromagnetic simulations, and so on. Wide ranges for parameters are set during the screen testing: the TSG is from 10 nm to 50 nm, the SSG is from 20 nm to 80 nm, the MPTH is from 15 nm to 35 nm, the LSFA is from 20^{o} to 40^{o}, the MPTA is from 0^{o} to 40^{o}, and the MPFA is from 0^{o} to 40^{o}. A set of head fields are generated according to the above values, and the strength of the maximum write fields are found to be from 1600 Oe to 11.5 kOe.

Determination of design window and determination of levels for design parameters

From the screen testing, the strength of the write field is one of the primary factors, on which the writeability depends. Magnetic recording does not happen with a write field of 1.6 kOe. With consideration of the generated write field, the TSG is adjusted from 20 nm to 40 nm, the SSG is from 40 nm to 60 nm, the MPTH is set from 0 nm to 20 nm, the LSFA is from 20^{o} to 40^{o}, the MPTA is from 35^{o} to 55^{o}, and the MPFA is from 30^{o} to 50^{o}. For the experiments in the next stages, these six parameters are set into five levels shown as Table I.

TABLE I
LEVELS FOR DESIGN PARAMETERS

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
TSG (nm)	20	25	30	35	40
SSG (nm)	40	45	50	55	60
MPTH (nm)	0	5	10	15	20
LSFA (^{o})	20	25	30	35	40
MPTA (^{o})	35	40	45	50	55
MPFA (^{o})	30	35	40	45	50

Performing of design of experiments

The orthogonal array [4] is used when the number of inputs to the system is relatively small, but too large to allow for exhaustive testing of every possible input to the systems. The permutations of factor levels comprising a single treatment are chosen such that their responses are uncorrelated and therefore each treatment gives a unique piece of information. The net effects of organizing the experiment in such treatments are that the same piece of information is gathered in the minimum number of experiments.

In this study, a standard orthogonal array P6L5 (6 parameters with 5 levels) is chosen to be used to conduct the DOE, which is composed of 25 combinations of all the design parameters and listed in Table II.

TABLE II
DESIGN OF EXPERIMENTS AND EXPERIMENTS RESULTS

	TSG	SSG	MPTH	LSFA	MPTA	MPFA	SNR (dB)	BER
1	20	40	0	20	35	30	13.8	0.00082
2	20	45	10	35	55	35	13.1	0.00154
3	20	50	20	25	50	40	13.0	0.00151
4	20	55	5	40	45	45	14.0	0.00069
5	20	60	15	30	40	50	14.0	0.00074
6	25	40	20	35	45	50	12.9	0.00161
7	25	45	5	25	40	30	13.4	0.00119
8	25	50	15	40	35	35	13.2	0.00151
9	25	55	0	30	55	40	12.8	0.00181
10	25	60	10	20	50	45	14.2	0.00071
11	30	40	15	25	55	45	12.5	0.00237
12	30	45	0	40	50	50	13.4	0.00127
13	30	50	10	30	45	30	12.4	0.00242
14	30	55	20	20	40	35	11.7	0.00361
15	30	60	5	35	35	40	8.8	0.02355
16	35	40	10	40	40	40	12.7	0.00205
17	35	45	20	30	35	45	12.2	0.00300
18	35	50	5	20	55	50	13.3	0.00125
19	35	55	15	35	50	30	11.2	0.00638
20	35	60	0	25	45	35	13.7	0.00097
21	40	40	5	30	50	35	11.6	0.00476
22	40	45	15	20	45	40	11.9	0.00401
23	40	50	0	35	40	45	13.6	0.00113
24	40	55	10	25	35	50	13.0	0.00160
25	40	60	20	40	55	30	9.7	0.02079

Experiments and Results

In this study, the experiment includes several stages: the Finite Element Method (FEM) based head field generation; LLG-based micromagnetic simulation; SNR characterization; and BER computation by applying GFP model.

There are 25 head fields simulated using the FEM according to the combinations of the DOE.

Micromagnetic simulations based on the LLG equation [5] are carried out using the above 25 write head profiles. Each simulation generates a magnetization distribution of 500 random bits. We fix the media properties in the simulations: the grain size is of 8.6 nm with 0.4 nm grain boundary and the sigma of 8%; the saturation magnetization (Ms) of the media is 500 emu/cc; the anisotropy constant (Ku) of the media is 3.50 Merg/cc; Head Media Spacing (MHS) is 7 nm; and the bit length is 13 nm. Fig. 3 shows the sample micromagnetic simulation outputs for the 10th and 15th head fields in Table II respectively. The GFP models for each case are characterized by writing a block of 4 tracks × 1024 bits via the micromagnetic simulations on a distributed micromagnetic simulation system.

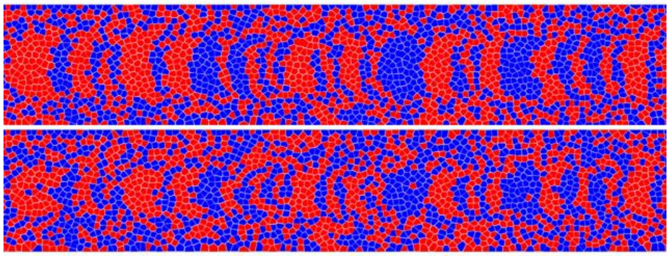

Fig. 3. Partial view of the micromagnetic simulation outputs for the head fields using the 10th (Top) and 15th (Bottom) head design.

The SNRs computed in this study are obtained from a signal-processing perspective. The signal is taken as the noise-free output y_k of the best fit linear response h to the input bits a_k, while the noise is taken as the difference between the noise-free signal and noisy observed signal r_k. The best fit linear response h is obtained by solving the Wiener-Hopf [6] equation that uses the autocorrelation matrix of a_k and the cross-correlation matrix between a_k and r_k. In the context of Fig. 4, the SNR is obtained as the ratio of the powers of y_k and e_k and represented as (1)

$$SNR^* = 10 \times \log_{10}\left(\frac{E\left(y_k^2\right)}{E\left(e_k^2\right)}\right). \tag{1}$$

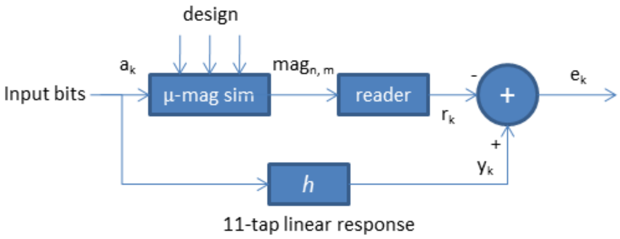

Fig. 4. Block Diagram showing components used in the SNR calculation.

After convolution of the media magnetization with the read head sensitivity function, a number of slices of the resulting array are taken. Down-sampling to baud rate ensues, followed by equalization and detection to arrive at an estimate of the BER while the SNR is also characterized. The process of BER calculation is shown as Fig. 5.

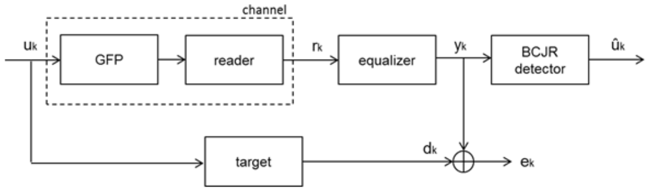

Fig. 5. Block Diagram showing components used in the BER calculation.

Fig. 6 shows one of the footprints of the GFP models and the contour of the flipping probability. The results of SNR characterization and BER calculation are listed as the right-hand columns in the Table II.

Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences between group means and their associated procedures (such as "variation" among and between groups), developed by R. A. Fisher [7]. ANOVAs are useful in comparing (testing) three or more means (groups or variables) for statistical significance.

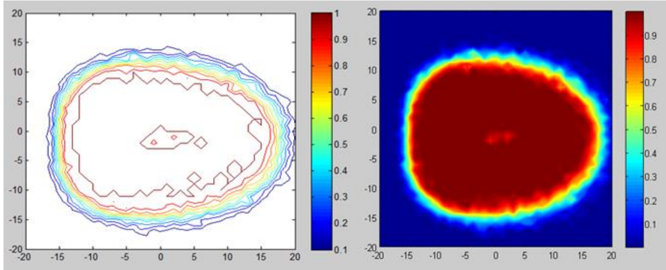

Fig. 6. Contour of flipping probability (left) and footprint of recording (right) from the GFP model.

One of the key features of the Taguchi method is the use of a Signal-to-Noise ratio parameter to transform the performance characteristic in the optimization process. To differ from the SNR which is used in read-back signal processing, the short-formed S/N is introduced. For the characteristics of SNR and BER, the S/Ns are classified as the Larger-the-Better and the Smaller-the-Better respectively. The equation for the Larger-the-Better is represented as (2) and the equation for the Smaller-the-Better is represented as (3).

$$SNR^* = -10 \times \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right). \tag{2}$$

$$SNR^* = -10 \times \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right). \tag{3}$$

where n is the number of repetitions, i is the index of experiments, and y_i is the optimization parameter of interest, which is SNR in (2) and BER in (3).

TABLE III
MEANS OF S/N FOR SNR

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
TSG	22.647	22.478	21.324	22.004	21.502
SSG	22.057	22.137	22.335	21.941	21.485
MPTH	21.573	21.636	22.309	21.949	21.487
LSFA	22.252	22.360	22.004	21.416	21.924
MPTA	21.621	22.317	22.247	22.032	21.738
MPFA	21.590	22.027	21.393	22.451	22.494

TABLE IV
MEANS OF S/N FOR BER

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
TSG	60.030	57.715	48.841	53.307	48.578
SSG	54.065	54.211	56.439	53.343	50.413
MPTH	55.750	51.751	56.252	52.670	49.047
LSFA	55.921	56.718	53.332	49.499	53.001
MPTA	51.422	56.522	55.918	53.543	51.065
MPFA	50.008	53.656	49.105	57.622	58.079

The mean S/N for a particular parameter at a particular value is simply taken over all values where the parameter holds the given value. For example, the level 1 value of SSG is 40 nm. The mean of the S/N for the SSG parameter at this value is taken by averaging the 1st, 6th, 11th, 16th and 21st rows in Table 2, where SSG equals to 40 nm. The average value of the S/N metric for the computed SNR and BER are shown in Table III and IV respectively.

By applying ANOVA, it can be determined which level the highest SNR and the lowest BER can be achieved for each parameter. From both of table III and table IV, The highest mean of S/N is achieved with TSG at level 1, SSG at level 3, MPTH at level 3, LSFA at level 2, MPTA at level 2, and MPFA at level 5 respectively.

The Sum of Squares (SS) is the sum of the squares of deviations of individual observations from the respective expected averages. When calculated in a statistical analysis, it reflects the effect of a design parameter influencing these observations. In the analysis of variance procedure one often uses SS to establish whether a particular design parameter is significant to the performance characteristics. The Mean Sum of Squares (MSS) is the average variability among observations obtained by dividing the corresponding SS by its Degrees of Freedom (DOF). It is noted that the DOF of a statistic shows the number of independent observations employed in calculating the statistic. The Percentage Contribution (PC) of a parameter represents how much the parameter effects on the SNR and the BER compared with other parameters. Table V lists the results of the ANOVA and the PC based on the experiments of SNR and BER.

TABLE V
PERCENTAGE CONTRIBUTION

Parameter	SS	DOF	MSS	PC (%)
TSG	2.5417	4	0.6354	32.14%
SSG	0.5288	4	0.1322	6.69%
MPTH	1.5090	4	0.3773	19.08%
LSFA	0.9035	4	0.2259	11.43%
MPTA	0.6284	4	0.1571	7.95%
MPFA	1.7956	4	0.4489	22.71%

Prediction and verification

In last stage, the levels for every parameter, at which the highest S/N is achieved, are determined. The corresponding values at the optimal solution are with TSG of 20 nm, SSG of 50 nm, MPTH of 10 nm, LSFA of 30^{o}, MPTA of 40^{o}, and MPFA 50^{o}. At this solution, the SNR and BER can be predicted by regressive analysis [3]. And the predicted SNR and BER at the optimal solution are 15.80 dB and 0.000266 respectively.

A verification process is performed by generating the new head field, running 500-bits micromagnetic simulation, and evaluating the SNR and BER. The verified SNR and BER are 14.35 dB and 0.000488 respectively. Although the validated SNR and BER are not as good as the predicted ones, they are still better than all the other head designs tested in Table II.

Comparison and Analysis

A comparison among the nominal design, the optimal design and a commercial head design is carried out. The SNRs and BERs are listed in TABLE VI.

From the TABLE V, it indicates that the TSG has the most significant influence on the SNR and BER while the SSG and the MPTA have the least contribution to the performance characteristics. We investigate the relationship between the TSG and the down-track field gradient. It is found that the TSG has a very nice alignment with the down-track field gradient, SNR and BER. The best gradient and strenth of write field are the main reasons why the best SNR and BER are achieved at the optimal design. Fig. 7 plots the down-track field gradient curves at the nominal design, the optimal design, and the commercial design.

It is also noted that all the experiments are based on the single track micromagnetic simulations. Therefore, the analysis result shows that the SSG is not critic to the recording performance. In future work, it becomes necessary to optimize the write head based on the multi-track recordings.

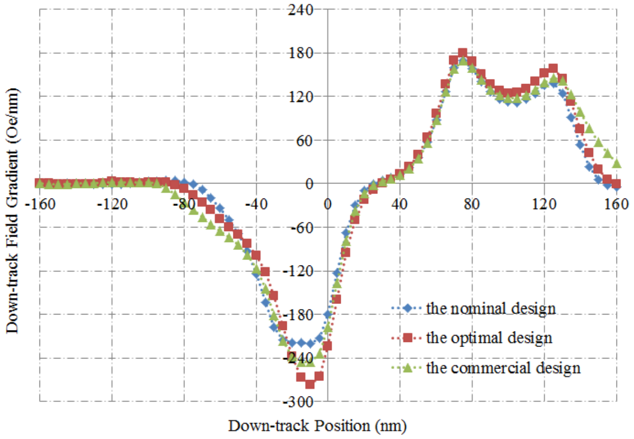

Fig. 7. Plots of the down-track field gradient with the nominal design, the optimal design, and the commercial design.

IV. CONCLUSION

In this study, we select six parameters from write head design for perpendicular magnetic recording, and conduct design of experiments. Through generating the various head fields, running micromagnetic simulations, and applying of the GFP model, we calculated the corresponding SNRs and BERs. An optimal design is obtained by ANOVA, and it is verified that the highest SNR and lowest BER are achieved at this optimal design. This study is successful and effective to search an optimal write head.

TABLE VI
COMPARISON OF SNR AND BER

	SNR	BER
The Nominal Design	12.43 dB	0.002426
The Optimal Design	14.35 dB	0.000488
The Commercial Design	13.54 dB	0.001062

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