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Physically Based Information Science of Magnetic Recording II. Physical Sources of Medium Noise

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Abstract— **A physically based model for a magnetic recording medium is augmented by the simulation of reading with a standard head model. The medium noise generated by this model comprises a repeatable component and a non-repeatable component. The repeatable component of medium noise is partially statistically characterized. The non-repeatable component of medium noise is shown to depend on the intrinsic properties of the recording medium in a manner consistent with the medium's computed storage capacity bound.**

I. Introduction

The objective of the read process in magnetic recording systems is to determine from a read-back voltage waveform a best estimate of an information-bearing sequence previously stored in the magnetization patterns of the recording medium. In designing systems to achieve this objective, a statistical characterization of the relationship between the stored information and the observed waveforms is an indispensable tool. Characterizing the statistics of the observed waveforms includes characterizing the statistics of the medium noise.

Medium noise may be characterized by experimental observation. Recent measurements have indicated that medium noise comprises a repeatable component and a non-repeatable component [1]. The repeatable component is thought to arise from local magnetic microstructure. Hoinville proposed a model to generate simulated medium noise with similar properties [2]. In Hoinville's model, the non-repeatability of medium noise from one write to the next is generated by a random perturbation on the direction of magnetization of magnetic domains. The work of Zhu and Bertram characterizes medium noise on a firmer physical basis [3]. They demonstrate a dependence of the observed medium noise on the intrinsic properties of the recording medium. In this paper, we follow the latter strategy, using a model based on the physics of magnetically interacting domains. Our results show a division of medium noise into repeatable and non-repeatable components as do Hoinville's simulations and measurements.

II. Noise-Free Simulation

A. Reading Simulation

Our model for magnetic recording media [4] represents the recording medium as a set of tiles which cover the planar surface of the medium. These tiles form a rectangular grid. Each tile is X m long and Z m wide. Each tile is uniformly magnetized in one of two directions along its easy axis of anisotropy. All tiles are assumed to have the same magnetization magnitude, M A/m. Then,

$$\begin{aligned} M_x(x,z) &= M \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} s_{kl} \cos\theta_{kl} \\ &\cdot [u(x-kX) - u(x-(k+1)X)] \\ &\cdot [u(z-lZ) - u(z-(l+1)Z)]. \end{aligned} \quad (1)$$

In this expression, we have made use of the unit step function, $u(x)$. The variables $\{s_{kl}\}$ have values of ± 1, and they indicate which of the two directions along the easy axis is the direction of magnetization. The variables $\{\theta_{kl}\}$ take values between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$ and they indicate the angle the easy axis makes with x-axis.

The simulations described in this paper compute the read-back voltage generated by a recording head. This computation is made using the reciprocity theorem and the Karlqvist head model. The read simulation with the usual thin film approximations and the notation of [5] is

$$\begin{aligned} v(t) &= \frac{\mu_0 V \delta H_g M Z}{\pi} \sum_k \sum_l s_{kl} \cos\theta_{kl} \\ & [\tan^{-1} \frac{g/2 + Vt - kX}{d+\delta/2} \\ &- \tan^{-1} \frac{g/2 + Vt - kX - X}{d+\delta/2} \\ &+ \tan^{-1} \frac{g/2 - Vt + kX}{d+\delta/2} \\ &- \tan^{-1} \frac{g/2 - Vt + kX + X}{d+\delta/2}]. \end{aligned} \quad (2)$$

An approximation for this expression is

$$v(t) = \sum_{k=-K}^{K-1} f(t - k\frac{X}{V}) \sum_{l=-L}^{L-1} s_{kl} \cos\theta_{kl}, \quad (3)$$

with $f(\cdot)$ appropriately defined dependent on the parameters of the head, medium, and the head-medium interface. The inner sum is truncated to limit the sources of the read-back voltage waveform to a track of finite width. The outer sum is truncated at a value of K large enough to achieve the desired precision.

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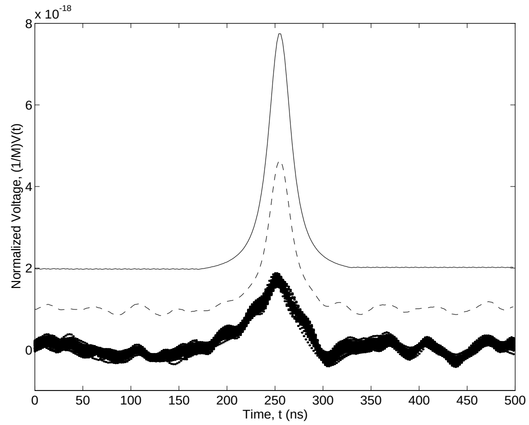

Fig. 1. Illustrations of medium noise

B. Ideal Recording

The ideal view of the inductive read process assumes a written track comprises magnetized regions of opposite direction. The regions are assumed to be magnetized perfectly along the track, in one direction or the opposite. Furthermore, the magnetization is assumed to be fully saturated, and the transition from one region to the next is assumed to be perfectly sharp. Under these assumptions, a read-back waveform may be predicted as a deterministic function.

These ideal assumptions may be reflected in (3) by placing appropriate constraints on the $\{s_{kl}\}$ and $\{\theta_{kl}\}$. In particular, let

$$\theta_{kl} = 0, \forall k, l \in \mathbf{Z}, \tag{4}$$

and let the $\{s_{kl}\}$ be determined by an information-bearing sequence $\{b(n)\}_{n=0}^{n=N-1}$ from $\{0,1\}^N$, written with the length of a "bit" on the medium surface of B m:

$$s_{kl} = (-1)^{b(\lfloor kX/B \rfloor)} \doteq s(k). \tag{5}$$

Together these constraints lead to a simple computation of the ideal read-back voltage waveform:

$$v_I(t) = 2L \sum_k s(k) f(t - k\frac{X}{V}). \tag{6}$$

The simplest non-trivial example of an ideal read-back voltage waveform is an isolated transition. The solid-line waveform of Fig. 1. illustrates an ideal transition at $t = 255$ ns. The parameters of the simulation are chosen to represent typical values for magnetic recording systems with the exception of the head gain H_g which is assigned an arbitrary value of unity. Thus, the amplitude of the read-back voltage waveforms in this paper is accurate only to within a scale factor. The waveforms in Fig. 1 are plotted with a vertical offset so as not to overlap.

III. Medium Noise

The read-back voltage waveforms observed in magnetic recording systems will differ from the ideal waveform in a number of ways. The differences due to non-ideal magnetization patterns are medium noise.

Our model neatly divides the differences of the magnetization pattern from the ideal into two categories. First of all, the easy axes of the tiles may not be aligned with the recording track. That is, the $\{\theta_{kl}\}$ may have non-zero values. The second category corresponds to the set of tile magnetization directions, represented by the $\{s_{kl}\}$. Though the pattern may be written according to (5) to store an information-bearing sequence, such a pattern may not be a stable magnetization configuration given the interacting magnetic forces among the tiles.

A. Repeatable Medium Noise

First we examine the effect on the read-back voltage signal of non-zero values of the variables $\{\theta_{kl}\}$. In the ideal case, all the tiles have their easy axes aligned with the recording track—an oriented medium. To represent random variations in the manufacture of an oriented medium, assume that the $\{\theta_{kl}\}$ are independent random variables.

Then, because the magnetization pattern is a function of random variables, the read-back voltage waveform is a random process, partially characterized by its statistics,

$$E\{v(t)\} = E\{\cos\theta\} v_I(t), \tag{7}$$

$$C_v(t_1, t_2) = 2LVar\{\cos\theta\} \sum_k f(t_1 - k\frac{X}{V}) f(t_2 - k\frac{X}{V}). \tag{8}$$

As an example, when the $\{\theta_{kl}\}$ are distributed uniformly, the expected transition waveform is the ideal transition waveform scaled by a factor of $2/\pi$.

The waveform is a random process only in the sense that the randomness characterizes the ensemble behavior of many transitions written at many positions on the medium. If the read head can be placed at a known position, and, in the limiting case, the angles $\{\theta_{kl}\}$ are known, then the read-back voltage waveform is deterministic, though its shape depends on the local features and is not the ideal shape. It is in this sense that this component of medium noise is repeatable. Some work on exploiting this repeatability using linear filters is presented in [6].

B. Non-Repeatable Medium Noise

The second category of medium noise is that noise due to the difference between the magnetization pattern written and a pattern which remains stable over time. This difference is due to the natural relaxation of the system of interacting magnetic tiles to a state of local minimum energy. The tile interactions include the effects of magnetostatic and exchange fields, and anisotropy energy is accounted for through use of a Stoner-Wohlfarth astroid as a threshold on reversal. The simulated relaxation process may be viewed as a time sequence of values $s_{kl}[n]$. At each time step n, one tile (k,l) is selected at random and examined to determine if reversing the value of s_{kl} will decrease the total energy of the system. If so, then the reversal is performed. This process continues until a stable state, denoted $\{s_{kl}[\infty]\}$, is reached. Then,

$$v(t) = \sum_k f(t - k\frac{X}{V}) \sum_l s_{kl}[\infty] \cos\theta_{kl}. \qquad (9)$$

In general, many stable patterns are possible final states of a natural evolution from a given initial written state. The final pattern is an unpredictable outcome. This source of medium noise is non-repeatable.

Analysis of (9) is quite complicated due to the mutual dependence of all the $\{s_{kl}[\infty]\}$ on each other and on the $\{\theta_{kl}\}$. Several simulations of the model give a qualitative sense of the ensemble behavior. It is interesting to compare these results with the capacity bound limits reported for this medium model in [7].

Fig. 1 illustrates the variability of the read-back voltage waveforms due to medium noise. The dashed waveform is the read-back voltage of a transition at a position on a non-oriented medium (that is, θ_{kl} uniformly distributed). The dotted waveforms are fifty realizations of the read-back voltage after the medium is allowed to relax to a stable magnetization pattern. The amplitude of the pulse is reduced because the sharpness of the transition is diminished when the tiles near the transition reverse their direction of magnetization. The variability of the waveform from one realization to the next is visible in the figure. However, there are also features which all of the realizations share. These shared features derive from the common starting point of all the realizations, determined by the set of easy axis orientation angles in this patch of the recording medium and the initial magnetization pattern written on the patch. These realizations, then, illustrate the point of view that medium noise consists of a non-repeatable part combined with a repeatable part.

The non-repeatable part of the medium noise is related to the number of stable patterns which the medium can support. The number of stable patterns in turn determines the fundamental upper limit on the storage capacity of that medium by arguments presented in [7, 8]. Fig. 2 illustrates the non-repeatable medium noise component for three media with different intrinsic parameters. Ensembles of ten realizations each of read-back voltage waveforms from an isolated transition are displayed for these three media. The waveforms are vertically offset so as not to overlap. From top to bottom, the ensembles exhibit an increasing effect of non-repeatable medium noise. Also from top to bottom, the computed storage capacity limits for these media decrease.

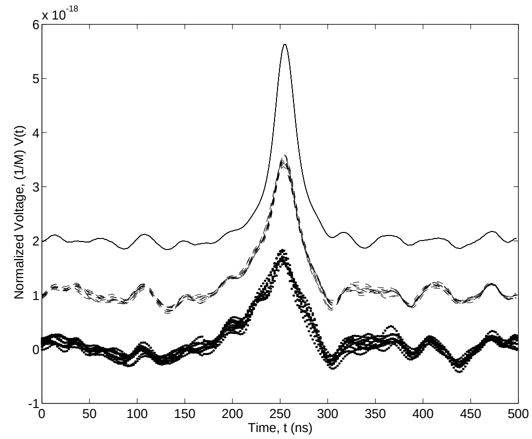

Fig. 2. The effect of storage capacity bound on non-repeatable medium noise.

IV. Conclusions

Using a standard model for the recording head and the reciprocity theorem, we have developed a computer simulation of the voltage waveforms read from a recording medium represented by our model. The medium noise computed exhibits both repeatable and non-repeatable components as observed in experiments. The non-repeatable component has greater effect as the storage capacity bounds decrease.

The repeatable component of medium noise has been partially characterized in its statistics. The statistics of the non-repeatable component of the medium noise remains an open problem.

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