Measured and Modeled responses for Heat Assisted Magnetic Recording up to Ultra-high Areal Densities

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While current magnetic recording components are still far from able to support user areal densities of 10 Terabits per square inch, it is nevertheless instructive to examine the behavior of readback waveforms as such extreme densities are approached. Waveforms from a contemporary shingled Heat Assisted Magnetic Recording (HAMR) system are captured and separated into linear & nonlinear signal components, inter-track interference (ITI), signal-dependent media noise, and head/electronic noise. These are tracked and compared with modeled behavior as media areal-density (FCI x TPI) is gradually increased. The modeled signal and noise are based on the reader response being approximated as the difference of two 2D Gaussians. The model agrees quite well all the way from 1 Tbit/in^2 to 10 Tbit/in^2 At the extreme of 10 Tbit/in^2, the signal is still clearly identifiable and is well-behaved with minimal distortion. It is however completely overwhelmed by high levels of stationary media noise and, to a lesser extent, inter-track interference and then head/electronic noise.

***Index Terms*— Hard Disk Drives, Heat Assisted Magnetic Recording, Recording Channel**

I. Introduction

Areal Densities of 10 Terabits per square inch remain a very distant goal for hard disk drives (HDD). However, it is still important to explore this regime to understand the opportunities for advanced coding and detection techniques [1]. In the 2000s, there was great optimism as rapid increases in areal density occurred corresponding with the introduction of several new technologies, notably: perpendicular recording, tunnel-junction heads, and fly-height control [2,3]. But over the last decade progress has slowed [4], and today's drives ship at a little more than 1 Tbit/in^2. Recently, Heat Assisted Magnetic Recording (HAMR) has been introduced with a promise to revitalize the industry [5]. Early shipments of HDDs with HAMR are already offering significantly higher areal-densities and capacities, though some of the challenges and practical limitations of the technology are also becoming apparent [6].

In this paper we examine the behavior of signals, interference, and noise on a contemporary shingled HDD recording channel up to extreme media densities (FCI x TPI) of 10 Tbit/in^2. These measurements are matched with a simple model based on 2D Gaussian pulses. [*Note: 'media densities' refers to the product of flux-changes per inch (FCI) and tracks per inch (TPI) and certainly not to the ability to store user data at such densities.*]

II. Modelling of the Readback Response as the Difference of Two 2D Gaussians

For practical reasons, in HAMR, the soft magnetic underlayer is spaced relatively far below the recording layer [5]. It does play a role in enhancing the write field from the relatively large write head but plays no appreciable role in the readback process [7]. For this reason, the reader sensitivity function can be modeled considering the recording layer alone. In particular, it can be modeled in terms of the *difference* between magnetic charges at the top of the recording layer and ideally identical charges at the bottom of the recording layer.

Classically, the read sensitivity function would be derived starting with Lorentzian type functions or, in the frequency domain, with the corresponding exponentials [7]. Indeed, for a magnetic spacing, d, and a perpendicular media thickness, δ, the vertical field component has the rather elegant form

$$\frac{d}{(d^2+r^2)^{3/2}} - \frac{d+\delta}{((d+\delta)^2+r^2)^{3/2}} \overset{FFT}{\Longleftrightarrow} e^{-\kappa d} - e^{-\kappa(d+\delta)}$$

The left side represents the spatial domain with $r^2 = x^2 + y^2$ (down-track and cross-track, respectively). The right side represents the frequency domain with $\kappa^2 = k_x^2 + k_y^2$ (down-track and cross-track spatial frequencies, respectively). The 'FFT' arrow indicates a 2D Fourier transform relationship. *[Note: for clarity, all the various scaling constants have been omitted throughout the digest]*

However, the expression above does not fit the measured spectra well. The reader itself includes a finite gap-length and finite shield thicknesses and has a finite sensor-width. Also, the writing process has a finite resolution ('a-parameter') and a finite write-width with pronounced transition curvature, etc. These result in a more Gaussian-like shape [8] and so, instead, we base the analysis on the *difference of two 2D Gaussians*

$$\frac{e^{-(r/d)^2}}{d^2} - \frac{e^{-(r/(d+\delta))^2}}{(d+\delta)^2} \overset{FFT}{\Longleftrightarrow} e^{-(\kappa d)^2} - e^{-(\kappa(d+\delta))^2}$$

An advantage of using Gaussians is that both the time-domain and the frequency domain responses have the same Gaussian form. Furthermore, Gaussians are separable, for example, $e^{-(r/d)^2} = e^{-(x/d)^2}e^{-(y/d)^2}$. This allows us to apply a 1D Fourier transform to just the down-track direction (x-axis).

$$e^{-(kd)^2}.\frac{e^{-(y/d)^2}}{d} - e^{-(k(d+\delta))^2}.\frac{e^{-(y/(d+\delta))^2}}{d+\delta}$$

This expression describes the frequency response for an impulse of magnetization (i.e. a tiny grain with height, δ)

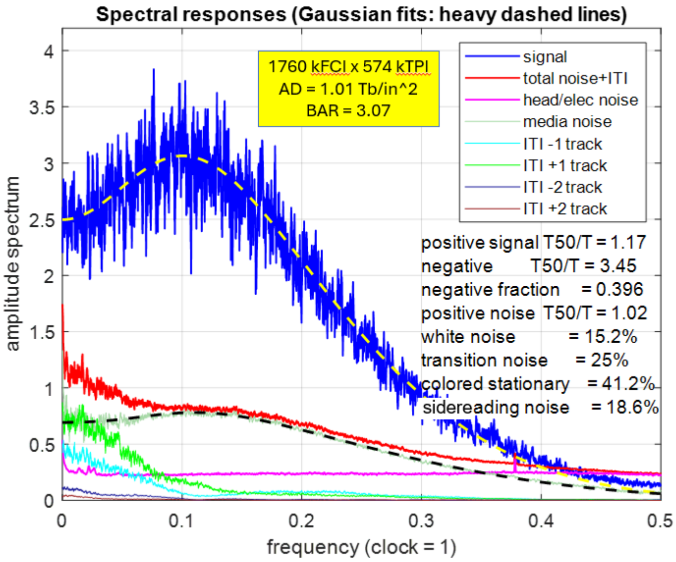

Fig. 1. Signal, interference, and noise spectra evaluated at the 1 Tb/in^2 base density. The heavy dashed lines are the model fits for the signal and media noise. "T50/T" is a more familiar measure that describes the width (proportional to α, β, or γ) of the corresponding 2D Gaussians.

passing under or near the reader. For a finite width written track extending from cross-track position y_1 to y_2, the integral gives

$$e^{-(kd)^2}\left[\mathrm{erf}\left(\frac{y_2}{d}\right) - \mathrm{erf}\left(\frac{y_1}{d}\right)\right] - e^{-(k(d+\delta))^2}\left[\mathrm{erf}\left(\frac{y_2}{d+\delta}\right) - \mathrm{erf}\left(\frac{y_1}{d+\delta}\right)\right]$$

With the assumption that the media noise is uncorrelated and stationary, we can also derive an expression for the media noise

$$\frac{1}{d\sqrt{2}}e^{-2(kd)^2} - \frac{2}{\sqrt{d^2+(d+\delta)^2}}e^{-k^2(d^2+(d+\delta))^2} + \frac{1}{(d+\delta)\sqrt{2}}e^{-2(k(d+\delta)^2}$$

The quantities d and δ may no longer be directly equal to the physical distances they are supposed to represent. But, as fitting parameters, they are valuable for matching to measured spectra and in observing trends as densities are pushed to the extreme.

III. Measurements and Model Fitting

Measurements are made on a contemporary HAMR HDD with shingled recording at media densities covering the range from 1 Tb/sq.in. to over 10 Tbit/in^2. Waveforms are captured at 10 GigaSamples/s. The subsequent filtering and synchronous bit-rate sampling operations are conducted in software before the waveforms are analyzed. The random data patterns on five consecutive shingled tracks are known. The read-back waveform is taken on the center track and is captured twice so that head/electronic noise can be easily separated.

From the waveforms and the known written data, we can determine the wanted signal response and the distortion, and also the inter-track interference (ITI) from up to two tracks on either side. By subtracting the wanted signal, the ITI responses, and the head/electronic noise from the waveform spectrum, we are left with the media noise spectrum.

We fit the signal spectrum with the following expression with four free parameters: A and α representing the amplitude and time-domain width of the positive Gaussian pulse and similarly the fractional, b, and β describe the negative Gaussian pulse

$$A\left[e^{-(k\alpha)^2} - b e^{-(k\beta)^2}\right]$$

(the sinc function for random NRZ data is included separately).

The noise spectrum is modeled with two further parameters, C and γ representing amplitude and time-domain width of the effective positive Gaussian pulse characterizing the noise.

$$C\sqrt{\frac{1}{\gamma\sqrt{2}}e^{-2(k\gamma)^2} - \frac{2}{\sqrt{\gamma^2+\beta^2}}e^{-k^2(\gamma^2+\beta^2)} + \frac{1}{\beta\sqrt{2}}e^{-2(k\beta)^2}}$$

The noise differs from the signal in that it is the integral over all space and the DC response must be zero (no field from a uniform magnetized sheet). This removes one degree of freedom. We leave the noise free to assume a wider bandwidth than the signal since it does not include factors such as the writing resolution or written track-width. Accordingly, measurements show that the noise resolution, γ, is significantly narrower than the signal resolution, α. The broader negative pulse-width, β, will tend to swamp these other dimensions, however, and is assumed the same for both signal and noise.

IV. Results and Conclusions

Figure 1 shows the results of measurements at the starting density of 1 Tb/sq.in. At this low density, the wanted signal is clearly dominant. The ITI from the immediately adjacent tracks, ±1, is also seen clearly, but the ITI from tracks at ±2 is very small. Media noise dominates strongly over the ITI and head/ electronics noise. As shown, the model curves fit very closely at this low density, though slightly less well at extreme densities.

As densities increase, we see the wanted signal diminish, yet it does remain well-behaved with low levels of non-linear distortion (not shown). At no point is there any abrupt degradation or failure. As expected, the side-reading noise (ITI) increases with track-density and the head/electronic noise increases with data-rate, but the main feature is the increasing media noise. By 10 Tbit/in^2, the media noise is very much larger than the signal or any other component and it also shows very little dependence on the presence or absence of magnetic transitions in the data. The implications of these findings are to be discussed in a companion presentation [1].

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