Thermal Asperity Suppression Based on Least Squares Fitting in Perpendicular Magnetic Recording Systems

Piya Kovintavewat and Santi Koonkarnkhai

***Abstract*—Thermal asperity (TA) causes a major problem in data detection process. Without the TA detection and correction algorithm, the system performance (even with perfect synchronization) can be unacceptable, depending on how severe the TA effect is. This paper proposes a new method to suppress the TA effects in perpendicular magnetic recording channels. The TA detection is a threshold-based approach, while the TA correction is done by averaging the readback signal and applying a least squares fitting technique to estimate the TA signal. Then, the corrected readback signal is obtained by subtracting the TA-affected readback signal by the reconstructed TA signal. Results indicate that the proposed method performs better than the existing one in terms of bit-error rate, and is robust to changes in the peak TA amplitude.**

***Index Terms*—Thermal asperity, perpendicular magnetic recording, least squares fitting.**

I. INTRODUCTION

DURING read process, the magnetoresistive (MR) head senses the change in flux via the transitions of the magnetic pattern written on the disk surface, resulting in an induced voltage pulse called a transition pulse. When an asperity (or a surface roughness) comes into contact with the slider, both the surface of the slider and the tip of the asperity are heated, which results in an additive voltage transient known as thermal asperity (TA) in the readback signal.

Typically, a TA signal has a short rise time (60–150 ns) with a long decay time (1–5μs), and its peak TA amplitude could be 2 to 3 times the peak of the readback signal [1], [2]. The TA effect can cause a burst of errors in data detection, which could easily exceed the correction capability of the error correction code (ECC), and thus results in a sector read failure. Therefore, a method to suppress the TA effect is required, especically at high recording density.

Several TA detection and correction algorithms have been proposed in the literature to reduce the TA effect. Practically, the TA causes a shift in the baseline of the readback signal. The average value of the normal readback signal is zero, whereas that of the TA-affected readback signal is not. Thus, Klaassen and van Peppen [3] proposed the TA detection by looking at the baseline of the averaged readback signal, while the TA correction was performed by use of a high-pass filter. Dorfman and Wolf [2] proposed a method to combat with the TA effect by passing the TA-affected readback signal through a filter $(1-D)$, where D is a delay operator. This method has been tested with an EPR4 target in longitudinal recording channels, where the number of bits corrupted by the TA effect is dramatically reduced. Nonetheless, this method is not suitable for a perpendicular recording channel because this channel contains a d.c. component.

Recently, Fatih and Erozan [4] proposed a TA detection and correction method for perpendicular recording channels by use of different low-pass and high-pass filters. Finally, Mathew and Tjhia [5] proposed a simple method to mitigate the effect of the TA in perpendicular recording channels, as described in Section III. This paper presents a new and simple method to suppress the TA effect based on a least squares (LS) fitting technique [6]. We also propose two options to reduce the complexity of the proposed TA suppression method, which can provide satisfactory bit-error rate (BER) performance and also robustness to changes in the peak TA amplitude.

This paper is organized as follows. After describing a channel model in Section II, Section III briefly explains how an existing method to mitigate the TA effect works. Section IV presents the proposed TA suppression method. Simulation results are given in Section V. Finally, Section VI concludes this paper.

II. CHANNEL MODEL

Fig. 1 illustrates a perpendicular recording channel model. A binary input data sequence $c_k \in \{\pm 1\}$ with bit period T is filtered by an ideal differentiator $(1-D)/2$ to form a transition sequence $d_k \in \{-1, 0, 1\}$, where $d_k = \pm 1$ corresponds to a positive or a negative transition, and $d_k = 0$ corresponds to the absence of a transition. The transition sequence d_k passes through a perpendicular recording channel whose transition response is given by $g(t) = \mathrm{erf}(2t\sqrt{\ln 2}/\mathrm{PW}_{50})$ [7], where $\mathrm{erf}(\cdot)$ is an error function defined as $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-z^2}dz$, and PW_{50} determines the width of the derivative of $g(t)$ at half its maximum. In the context of magnetic recording, a normalized recording density is defined as ND = PW_{50}/T, which determines how many data bits can be packed within the resolution unit PW_{50}. Thus, the TA-affected readback signal, $p(t)$, can be written as

$$p(t) = \sum_k d_k g(t-kT) + n(t) + u(t), \tag{1}$$

where $n(t)$ is additive white Gaussian noise (AWGN) with two-sided power spectral density $N_0/2$, and $u(t)$ is a TA signal.

We consider a widely used TA model described by Stupp *et al.* [1] as depicted in Fig. 2 because it fits captured spin stand data and drive data very well [4]. This TA signal has a short rise time with a long decay time, and its effect is assumed to decay exponentially, which can be modeled as

$$u(t) = \begin{cases} A_0 t/T_r, & 0 \le t \le T_r \\ A_0 \exp(-(t-T_r)/T_d), & T_r < t \le T_f \end{cases} \tag{2}$$

where A_0 is the peak TA amplitude, T_r is a rise time, and T_d is a decay constant. In this paper, the TA duration is assumed to be $T_f = T_r + 4T_d$ [5], where a decay time of $4T_d$ is sufficient because it will reduce the amplitude of the TA signal to approximately 1.8% of its peak amplitude.

At the receiver, the readback signal $p(t)$ is filtered by a seventh-order Butterworth low-pass filter (LPF), and is then sampled at symbol rate of 500 Mbps [5], assuming perfect timing. The sampler output, y_k, is fed to a TA detection and correction block to obtain a sequence s_k. Hence, the sequence s_k is equalized such that the output sequence, z_k, resembles the desired sequence, r_k. Eventually, the Viterbi detector performs sequence detection to determine the most likely input sequence.

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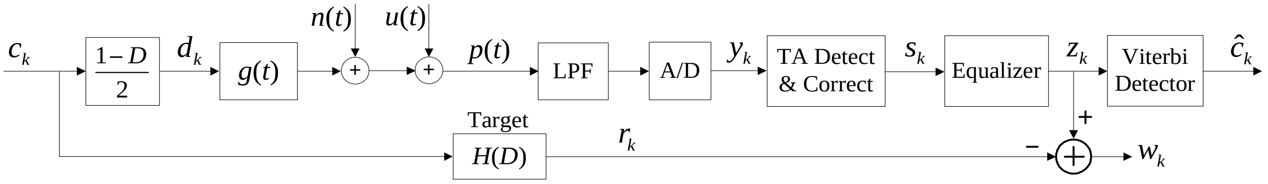

Fig. 1. Channel model with target design

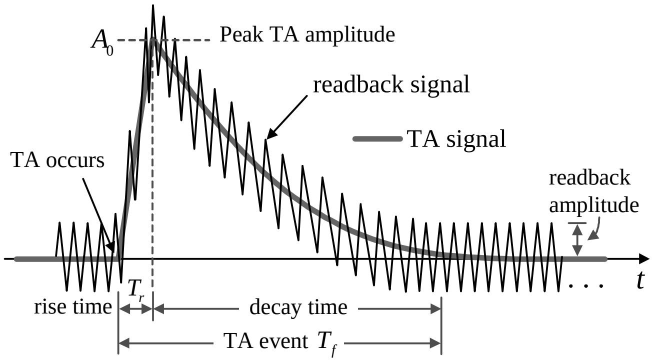

Fig. 2. A widely used TA signal, $u(t)$.

III. EXISTING TA SUPPRESSION METHOD

In this paper, we consider the method presented in [5] as the existing TA suppression method because of its simplicity and robustness to changes in the peak TA amplitude. This is done by first finding the average value of the readback signal, q_k, from

$$q_k = q(kT) = \frac{1}{L} \sum_{i=k-\beta}^{k+\beta} y_i, \tag{3}$$

where y_i is the i-th sample of the readback signal, β is an integer, and $L = 2\beta + 1$ is the window length for computing $\{q_k\}$. Then, a TA is detected if $q_k \geq m_1$, where $m_1 > 0$ is a threshold value. To make the TA detection more accurate [5], another criterion is utilized such that the readback signal y_k must exceed a particular threshold value m_2 for a few consecutive samples, i.e., $\{y_k\} \geq m_2$, where $m_2 > 0$.

The TA correction is performed by bringing the baseline of the TA-affected readback signal back to zero [5]. Since the TA signal can be reconstructed from $\{q_k\}$, the corrected readback signal is obtained by subtracting the TA-affected readback signal by the reconstructed TA signal.

IV. PROPOSED TA SUPPRESSION METHOD

The proposed method employs the same TA detection as used in [5]. However, after the TA is detected, the LS fitting technique is utilized to reconstruct the TA signal based on $\{q_k\}$. This can be achieved by estimating the TA signal during a rise time and a decay time, where the TA signal during a rise time is approximately linear, while that during a decay time is exponentially decay [1].

A. Estimate the TA Signal During a Rise Time

We use the average value of the readback signal, q_k, at the time where the TA is detected until it reaches its maximum value. Then, the estimated TA signal during a rise time, $\hat{u}_r(t)$, is obtained based on a linear LS fitting technique [6], i.e.,

$$\hat{u}_r(t) = at + b, \tag{4}$$

where a and b are constants, which can be found by solving

$$\begin{bmatrix} \sum_{i=1}^{n} t_i^2 & \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i & n \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} t_i q_i \\ \sum_{i=1}^{n} q_i \end{bmatrix}, \tag{5}$$

where $q_i = q(iT)$ is the i-th average value of the readback signal, $t_i = iT$ is the time index associated with q_i, and n is the number of samples used to construct $\hat{u}_r(t)$.

B. Estimate the TA Signal During a Decay Time

The samples $\{q_k\}$ starting from its maximum value until the end of a TA event are used to approximate the TA signal during a decay time, $\hat{u}_d(t)$, based on an exponential LS fitting technique [6], i.e.,

$$\hat{u}_d(t) = A \exp(Bt), \tag{6}$$

where $A = \exp(x)$ and B are constants, which can be obtained by calculating

$$x = \frac{\sum_{i=1}^{m} t_i^2 q_i \sum_{i=1}^{m} (q_i \ln q_i) - \sum_{i=1}^{m} t_i q_i \sum_{i=1}^{m} (t_i q_i \ln q_i)}{\sum_{i=1}^{m} q_i \sum_{i=1}^{m} (t_i^2 q_i) - \left\{\sum_{i=1}^{m} (t_i^2 q_i)\right\}^2}, \tag{7}$$

and

$$B = \frac{\sum_{i=1}^{m} q_i \sum_{i=1}^{m} (t_i q_i \ln q_i) - \sum_{i=1}^{m} t_i q_i \sum_{i=1}^{m} (q_i \ln q_i)}{\sum_{i=1}^{m} q_i \sum_{i=1}^{m} (t_i^2 q_i) - \left\{\sum_{i=1}^{m} (t_i^2 q_i)\right\}^2}, \tag{8}$$

where m is the number of samples used to construct $\hat{u}_d(t)$.

The whole estimated TA signal is obtained by combining (4) and (6) according to

$$\hat{u}(t) = \begin{cases} \hat{u}_r(t), & T_x \leq t \leq \hat{T}_r \\ \hat{u}_d(t), & \hat{T}_r < t \leq \hat{T}_f \end{cases}, \tag{9}$$

where T_x is the time TA is detected, $\hat{T}_r$ is the time when q_k reaches its maximum value, and $\hat{T}_f$ is the time when the magnitude of $\hat{u}_d(t)$ first becomes less than or equal to 0.01.

C. Mitigate the TA-Affected Readback Signal

After a TA is detected, the TA detection operation is disabled and the TA correction operation is activated for a duration of $\hat{T}_f$ so as to construct the estimated TA signal, $\hat{u}_k = \hat{u}(kT)$. Therefore, the corrected readback signal is given by

$$s_k = \begin{cases} y_k - \hat{u}_k, & \text{if TA is present} \\ y_k, & \text{if TA is absent} \end{cases}, \tag{10}$$

Note that most information is still preserved in the corrected readback signal. Hence, a sequence $\{s_k\}$ is fed to an equalizer, followed by the Viterbi detector.

V. NUMERICAL RESULTS

Consider a perpendicular recording channel at ND = 2.5. The signal-to-noise ratio (SNR) is defined as $\mathrm{SNR} = 10 \log_{10}(E_i/N_0)$ in dB, where E_i is the energy of the channel impulse response (the derivative of the transition response scaled by 2). The 11-tap equalizer and the 4-tap target were designed based on a minimum mean-squared

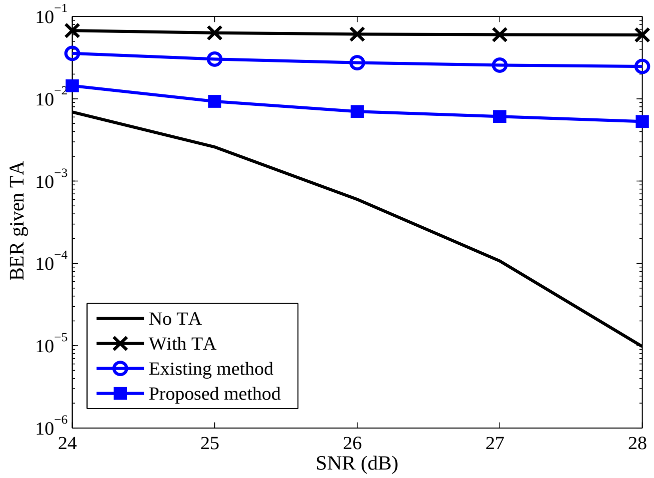

Fig. 3. Performance comparison.

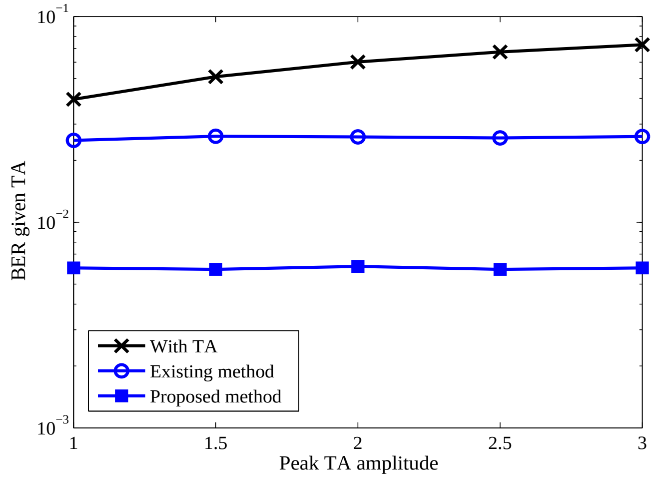

Fig. 4. BER performance with different peak TA amplitudes.

error (MMSE) approach [8] at the SNR required to achieve BER = 10^{-4} when a TA is absent. The 4-tap generalized partial response (GPR) target is $H(D) = 1 + 1.35D + 0.96D^2 + 0.33D^3$. Every 4096-bit data sector is corrupted by one TA signal, which is occurred at the 1000-th bit with A_0 = 2, T_r = 60 ns, and T_d = 0.5 μs (i.e., a TA event $T_f = 1030T$). This TA event can be considered as a worst case. We compute the BER of the system based on a minimum number of 500 4096-bit data sectors and 500 error bits, and call that number as "BER given TA." We use $L = 51$ to find $\{q_k\}$, and $m_1 = 0.5$ and $m_2 = 1.1$ for detecting a TA [5].

Fig. 3 compares the BER performance of different TA suppression methods as a function of SNRs. Apparently, without a TA suppression method, the system performance is unacceptable. Although the BER performance of the TA suppression methods is high, this is because the TA event used in our simulation is severe (i.e., all data sectors contain one TA event with a large amplitude and a long decay time). However, the proposed method still provides lower BER than the existing method. We also compare the BER performance of different methods as a function of peak TA amplitudes in Fig. 4 at SNR = 27 dB, where the system without a TA event yields BER = 10^{-4}. It is clear that the proposed method performs better than the existing one, and both are robust to changes in the peak TA amplitude.

With the LS fitting technique to approximate the TA signal, we can further reduce the complexity of the proposed method, while maintaining satisfactory BER performance. This can be achieved by two options. The first option is to use at least 60% of the total number of samples $\{q_k\}$ during a decay time to compute the coefficients A and B in (6). Then, the signal $\hat{u}_d(t)$ for a whole decay time can be constructed. The second option is that, instead of employing all T-spaced samples $\{q_k\}$ to construct the estimated TA signal $\hat{u}(t)$, we can only use (rT)-spaced samples, $\{q_{ir}\}$ for $r = 2, 3, 4$, or 5, to approximate the TA signal, based on an interpolation technique [9]. We did extensive simulations and found that (not shown here) the reduced-complexity TA suppression method based on these two options performs similar to the full-complexity TA suppression method described in Section IV.

VI. CONCLUSION

The TA effect can distort the readback signal to cause a sector read failure. We propose a new method to suppress the TA effect in perpendicular magnetic recording channels. Because the TA effect causes a shift in the baseline of the readback signal, a TA is detected when the average value of the readback signal, q_k, exceeds a particular threshold value. After the TA is detected, a sequence $\{q_k\}$ is used to construct the estimated TA signal, based on an LS fitting technique. Clearly, the proposed TA suppression method yields better BER performance than the existing one [5], and is also robust to changes in the peak TA amplitude.

It should be noted that the proposed method is not suitable for the hard drive that uses the tunneling MR heads because the TA response no longer looks like the one shown in Fig. 2 [10]. Thus, other techniques should be considered for such a hard drive [11].

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