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Effect of Bandpass Filters for TA Suppression in Perpendicular Recording System

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ABSTRACT

Thermal asperities (TAs) cause a crucial problem in magnetic recording systems because they can distort the readback signal to the extent of causing possible sector read failure. This problem becomes even more severe in perpendicular recording channels because these channels contain a d.c. component. This paper presents a novel TA suppression method by use of a bandpass filter to mitigate the TA effect. We also investigate the effect of different bandpass filters for TA suppression. Results indicate that the proposed TA suppression method using a bandpass filter polynomial $G(D) = (1+D)^2(1-D)$ yields lower bit-error rate than the existing ones at the expense of increased complexity, and is also robust to large peak TA amplitudes.

Keywords: Bandpass Filter, Perpendicular Recording, Thermal Asperity

1. INTRODUCTION

High-density magnetic recording systems use the magneto-resistive (MR) read head to sense flux directly via the transitions of the magnetization pattern, resulting in an induced voltage pulse called a transition pulse. When the slider comes into contact with an asperity (or a surface roughness) on the recording media, 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. The vulnerability of MR sensors to TA was identified shortly after their discovery [1].

In practice, the TA signal has a short rise time (50 – 160 ns) with a long decay time (1 – 5 μs), and its peak TA amplitude could be 2 – 3 times the peak of the readback signal [2, 3]. If precautions are not taken, 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 unrecoverable data. As the recording density keeps increasing, the flying height tends to be smaller and smaller. Hence, the chance that the slider contacts with the media is very high. Consequently, a method to suppress the TA effect is essential, especially for perpendicular recording channels.

Most of TA suppression methods proposed in the literature attempt to filter out the TA, lessen its duration, or employ a suitable equalization target to reduce the TA at the detector input [3]. Generally, the average value of the normal readback signal is zero, whereas that of the TA-affected readback signal is not, because the TA causes a shift in the baseline of the readback signal. Therefore, Klaassen and van Peppen [4] proposed the TA detection that looks at the baseline of the averaged readback signal, while the TA correction was performed by use of a high-pass filter. Dorfman and Wolf [3] 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.

For perpendicular recording channels, Fatih and Kurtas [5] proposed a TA detection and correction method by use of different low-pass and high-pass filters, whereas Mathew and Tjhia [6] proposed a simple threshold-based approach to detect and suppress the TA effect. Eventually, Kovintavewat and Koonkarnkhai [7] proposed a TA suppression method based on a least-squares fitting technique.

This paper presents a novel TA suppression method by use of a bandpass filter. The proposed method consists of two channels running in parallel. One channel is matched to the target response $H(D)$, while the other is matched to the target response $G(D)H(D)$, where $G(D)$ is a bandpass filter to mitigate the TA. Practically, the Viterbi detector (VD) [8] in the $H(D)$ channel has a lower bit-error rate (BER) in the absence of a TA, whereas that in the $G(D)H(D)$ channel has a lower BER in the presence of a TA. Therefore, the overall decoded bit stream is selected from these two VDs, depending on whether a TA is detected. We also investigate the effect of different bandpass filters for TA suppression.

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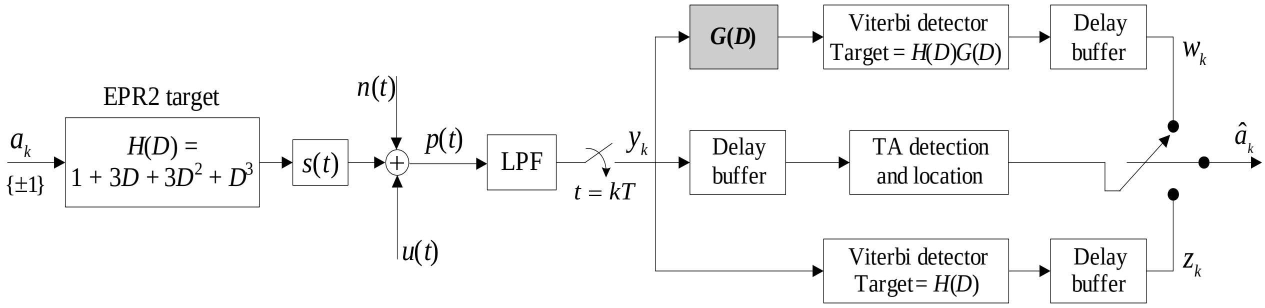

Fig.1: *A channel model with the proposed TA suppression method.*

The rest of this paper is organized as follows. After explaining the channel model in Section 2, Section 3 describes a widely used TA model. Section 4 presents the proposed TA suppression method. Numerical results and discussion are given in Section 5. Finally, Section 6 concludes this paper.

2. CHANNEL MODEL

Consider the perfectly equalized EPR2 channel model in Fig. 1, where the TA-affected readback signal can be written as

$$p(t) = \sum_k a_k h(t - kT) + n(t) + u(t) \tag{1}$$

where $a_k \in \{\pm 1\}$ is an input data sequence with bit period T, $h(t) = s(t)+3s(t-T)+3s(t-2T)+s(t-3T)$ is an EPR2 pulse, $s(t) = \sin(\pi t/T)/(\pi t/T)$ is an ideal zero-excess-bandwidth Nyquist pulse, $n(t)$ is additive white Gaussian noise (AWGN) with two-sided power spectral density $N_0/2$, and $u(t)$ is a TA signal.

At the receiver, the readback signal $p(t)$ is filtered by an ideal low-pass filter (LPF), whose impulse response is $s(t)/T$, to eliminate the out-of-band noise, and is then sampled at a sampling rate of 500 Mbps [6], assuming perfect synchronization. Thus, a sequence y_k is fed to different TA suppression methods, followed by the VD to determine the most likely input sequence.

3. THERMAL ASPERITY MODEL

This paper considers a widely used TA model described by Stupp *et al.* [2], as depicted in Fig. 2, because it fits captured spin stand data and drive data very well. Typically, the TA signal associated with the MR sensor head will have a short rise time with a long decay time, and its effect is assumed to decay exponentially, which can be modeled as [6]

$$u(t) = \begin{cases} A_0 \frac{t}{T_r} & 0 \le t \le T_r \\ A_0 \exp\left(-\frac{t-T_r}{T_d}\right) & T_r \le t \le T_f \end{cases}. \tag{2}$$

where $A_0 = \beta \sum_k |h_k|$ is the peak TA amplitude, $\beta \ge 0$ is a peak-factor, T_r is a rise time, and T_d is a decay constant. In this paper, the TA duration is

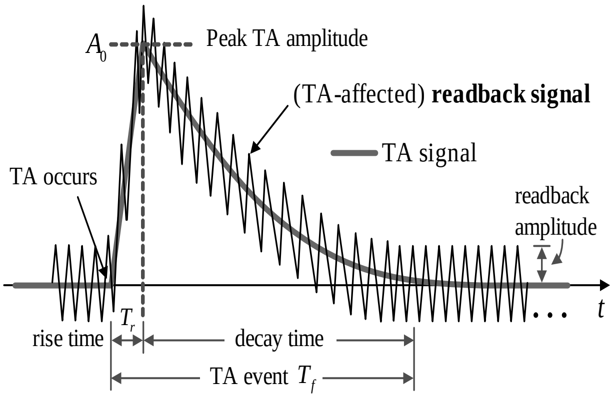

Fig.2: *TA signal associated with the MR sensor head.*

assumed to be $T_f = T_r + 4T_d$ [6], 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.

4. PROPOSED ALGORITHM

The proposed method is developed from the TA suppression methods presented in [3]. Specifically, the proposed method employs two VDs running in parallel as illustrated in Fig. 1. One channel is matched to the $H(D)$ target, while the other is matched to the $G(D)H(D)$ target equipped with a bandpass filter $G(D)$. Because the perpendicular recording channels have significant low-frequency content, we propose a bandpass filter $G(D)$ to eliminate a TA, while retaining most energy of the readback signal. In practice, the VD in the $H(D)$ channel has good performance when a TA is absent, whereas the VD in the $G(D)H(D)$ channel has good performance when a TA is present. Therefore, the overall decoded bit stream is chosen from the outputs of these two VDs. If a TA is detected, a decoded bit w_k is selected; otherwise, a decoded bit z_k is chosen.

To detect a TA, we first pass a sequence y_k through a digital lowpass filter to smoothen the readback signal, whose transfer function is given by [5]

$$F(z) = \frac{1}{m - (m-1)z^{-1}}, \tag{3}$$

where m determines the cutoff frequency. Next, we compute the average value of the readback signal, q_k, according to

$$q_k = \left(\frac{1}{L_1 + L_2 + 1}\right) \sum_{i=k-L_1}^{k+L_2} b_i, \tag{4}$$

where L_1 and L_2 are integers, and b_i is the i-th sample of the readback signal after filtering by an $F(z)$. As a result, a TA is detected if $q_k \geq m_1$, where m_1 is a threshold value. It can be shown that a large threshold will lead to a better AWGN performance at the expense of the TA performance. Conversely, a small threshold might lead to many false alarms, resulting in the output bits being w_k in the absence of a TA.

Based on extensive simulation, we found that m = 220, L_1 = 10, L_2 = 80, and m_1 = 1 are suitable parameters for this EPR2 channel since they can provide a good performance both in the presence and in the absence of TAs.

5. NUMERICAL RESULT

In simulation, every 4096-bit data sector $\{a_k\}$ is corrupted by one TA signal, which is occurred at the 1000-th bit with $\beta = 2$, $T_r = 60$ 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."

This paper compares the performance of the proposed TA suppression method with that of the methods proposed in [3] and [6]. The method presented in [3] is denoted as "Method 1" and that presented in [6] is referred to as "Method 2." Because the perpendicular recording channel contains a d.c. component, we propose a bandpass filter $G(D)$ of the form

$$G(D) = (1 + D)^i (1 - D)^j, \tag{5}$$

where i and j are integers, to mitigate a TA, while retaining most energy of the readback signal. It should be noted that the higher the values of i and j, the higher the complexity of the VD for the $H(D)G(D)$ channel. Therefore, for simplicity, we consider only the case where $i + j \leq 3$, specifically $G_1(D) = (1 + D)(1 - D)$, $G_2(D) = (1 + D)(1 - D)^2$, and $G_3(D) = (1 + D)^2(1 - D)$.

5.1 Uncoded System

We first compare the performance of the proposed TA suppression method with that of other methods in an uncoded system (i.e., a system without ECC) as shown in Fig. 1. The per-bit signal-to-noise ratio (SNR) is defined as

$$\frac{E_b}{N_0} = 10 \log_{10} \left(\frac{\sum_k |h_k|^2}{2\sigma^2} \right) \tag{6}$$

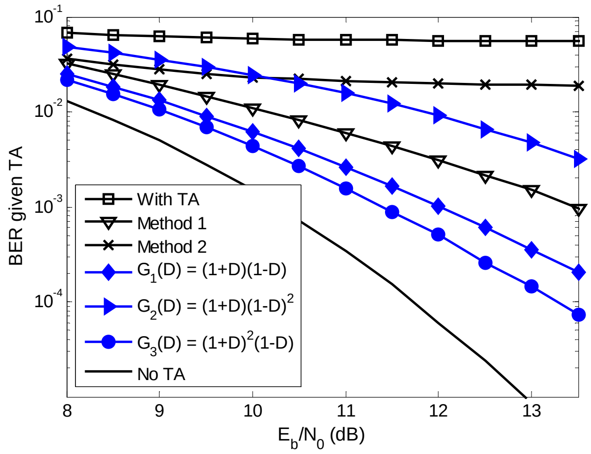

Fig.3: *Performance comparison of different TA suppression methods.*

in decibel (dB), where $\sum_k |h_k|^2$ is the energy of a channel and $\sigma^2 = N_0/(2T)$ is AWGN power. Figure 3 compares the BER performance of different TA suppression methods as a function of E_b/N_0's, where the system performance in the absence of TAs is referred to as "No TA." It is evident that without the TA suppression method, the system performance is unacceptable, denoted as "With TA." As shown in Fig. 3, the proposed method using $G(D)$ with parameter $i \geq j$ (i.e., $G_1(D)$ and $G_3(D)$) performs better than other methods. In addition, the proposed method using $G_3(D) = (1 + D)^2(1 - D)$ provides a lower BER than that using other $G(D)$'s. This is because a bandpass filter $G_3(D)$ can capture most energy of the readback signal as illustrated in Fig. 4. Clearly, the frequency response of a bandpass filter $G_3(D)$ gives a better match to that of the EPR2 channel than other $G(D)$'s. Furthermore, based on extensive simulation (not shown here), we found that using the bandpass filter $G(D)$ with parameters $i > 2$ and $j = 1$ in the proposed method can improve the system performance since its frequency response will have a much better match to the frequency response of the EPR2 channel.

We also compare the BER performance of different TA suppression methods as a function of peak-factors in Fig. 5 at $E_b/N_0 = 11.6$ dB, where the system without a TA event yields BER $\approx 10^{-4}$. It is obvious that the proposed TA suppression method using $G_3(D)$ performs better than other methods, and is robust to large peak TA amplitudes. This is again because the bandpass filter $G_3(D)$ can both eliminate the TA signal and preserve most energy of the readback signal if compared to other $G(D)$'s.

5.2 Coded System

We also investigate the performance of the proposed TA suppression method in a coded system, where an ECC is used to encode and decode a mes-

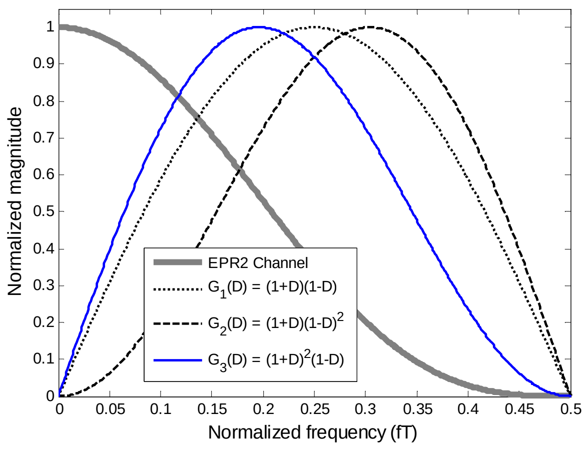

Fig.4: *Frequency responses of different bandpass filters.*

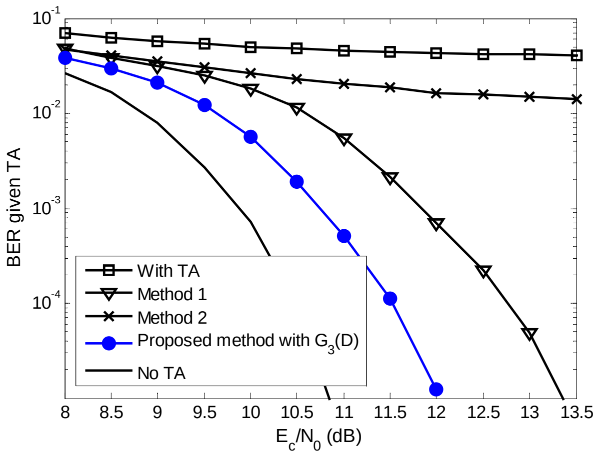

Fig.6: *Performance comparison of different TA suppression methods in coded systems.*

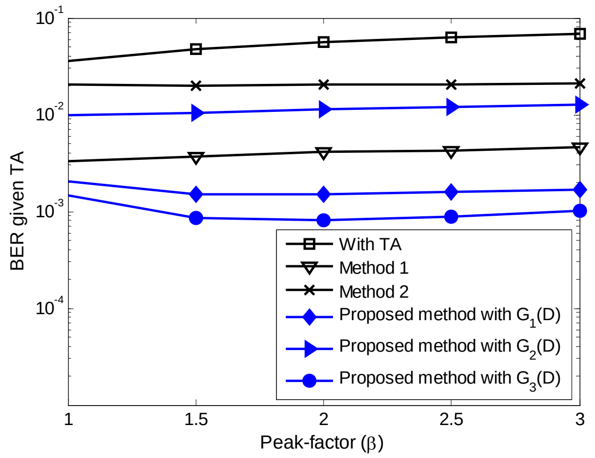

Fig.5: *BER performance with different peak-factors.*

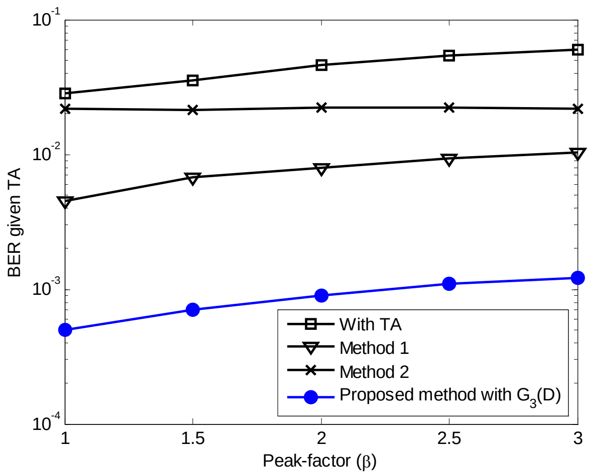

Fig.7: *BER performance with different peak-factors in coded systems.*

sage sequence x_k. In this paper, we focus on a widely used ECC in magnetic recording systems, namely, a Reed-Solomon (RS) code [9], because it can efficiently correct a burst of errors. Specifically, we consider a rate-223/255 coded system in which a block of 3568 message bits, x_k, is encoded by an RS code with parameters $(n, k) = (255, 223)$ [9], resulting in a coded block length of 4080 bits, a_k, as an input data sequence shown in Fig. 1. Similarly, the detected bits $\hat{a}_k$ in Fig. 1 are also decoded by the RS decoder to obtain an estimated message sequence $\hat{x}_k$.

To account for a code rate, the SNR used in a simulation of coded systems is defined as

$$\frac{E_c}{N_0} = \left(\frac{E_b}{N_0}\right) R \tag{7}$$

in dB, where $R = 223/255$ is a code rate for this simulation setup. Figure 6 compares the performance of different TA suppression methods in coded systems as a function of E_c/N_0's. In general, the BER performance of the coded systems is much better than that of the uncoded systems, especially at high SNRs, because the RS code can correct error bursts. Nonetheless, as depicted in Fig. 6, without efficient TA suppression methods, the BER performance is unacceptable, even in coded systems. It is also apparent that the proposed TA suppression method still performs better than the existing methods in coded systems. Specifically, a 1.7 dB gain at BER $= 10^{-4}$ can be obtained from the proposed method if compared to Method 1.

In addition, we also compare the BER performance of different TA suppression methods as a function of peak-factors for coded systems in Fig. 7 at $E_c/N_0 = 10.8$ dB, where the system without a TA event yields BER $\approx 10^{-5}$. Clearly, the proposed TA suppression method with a $G_3(D)$ filter performs better than Method 1 and Method 2.

Table 1: *Complexity of the Viterbi detector for $H(D) = 1 + 3D + 3D^2 + D^3$.*

Filter $G(D)$	Viterbi detector with $H(D)G(D)$ target	
	Target memories	Number of states in the trellis
$(1 - D)$	4	$2^4 = 16$
$G_1(D) = (1 + D)(1 - D)$	5	$2^5 = 32$
$G_2(D) = (1 + D)(1 - D)^2$	6	$2^6 = 64$
$G_3(D) = (1 + D)^2(1 - D)$	6	$2^6 = 64$

5.3 Note on Complexity

It is evident from Fig. 3 and Fig. 5 that a suitable filter $G(D)$ helps reduce the TA effect in the proposed TA suppression method at the expense of increased complexity. Table 1 compares the complexity of the VD with different $G(D)$ filters. Apparently, the VD with the $H(D)G_3(D)$ target has very high complexity because it requires 64 states in the trellis [8] in order to perform maximum-likelihood sequence detection.

Although $G_3(D)$ provides better performance than other $G(D)$'s, one needs to consider the implementation cost. In other words, all advantages gained by $G_3(D)$ need to be balanced against the increased implementation cost. For example, for our proposed method, $G_1(D)$ might be a good choice to be implemented in real systems instead of $G_3(D)$.

6. CONCLUSION

The TA effect can distort the readback signal to the extent of causing a sector read failure. This paper proposes a novel method using a bandpass filter to suppress the TA effect in perpendicular recording channels. Based on simulations with different bandpass filters, it can be concluded that the better the frequency response of the bandpass filter matches to that of the EPR2 channel, the better the system performance can be obtained. Clearly, the proposed TA suppression method with a suitable bandpass filter performs better than the existing ones for all peak TA amplitudes, and is also robust to large peak TA amplitudes. In addition, the system performance can be further improved by using a modified VD in the $H(D)G(D)$ channel to combat with the colored noise introduced by the $G(D)$ filter, as studied in [10].

Note that the proposed TA suppression method might not suitable for the disk drives that use the tunneling MR heads because the TA response no longer looks like the one shown in Fig. 2 [11]. As a consequence, other techniques should be considered for such a hard drive [12].

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