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Full Paper

Simple unstable baseline detection methods for perpendicular magnetic recording

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Abstract: Current hard disk drives employ a magneto-resistive head to read and write data. During the reading process, if the magneto-resistive head is unstable or has some defects, the readback signal will experience some missing data zones known as an unstable baseline (UB) event, which causes the signal amplitude to drop drastically and vary around the baseline at 0 volt. Thus, such defective heads must be detected and taken care of during the testing process before assembling a hard disk drive. This paper proposes three simple methods to detect the UB event that can be employed in the testing process when the data have a specific pattern, i.e. $4T$-pattern, where T is the bit period. The proposed methods can also be utilised to detect the UB event during normal operation when the data are random. Simulation results indicate that the methods can detect the short UB event (4-bit duration) with $4T$-pattern data and the 25-bit UB event with random data at 100% of detection.

Keywords: head instability, magneto-resistive head, perpendicular magnetic recording, unstable baseline

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INTRODUCTION

In perpendicular magnetic recording systems, when the magneto-resistive read head senses the change in a magnetic flux via the transition of the magnetisation pattern, an induced voltage pulse called a transition pulse is produced. Then a read channel transforms this induced voltage pulse into the output response known as a readback signal. If the magneto-resistive read head has some defects that come from the manufacturing process or are caused by electrostatic discharge effects, the quality of the readback signal will be poor, thus making a detector unable to decode data

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correctly. This problem is usually referred to as head instability, which yields several impacts in the hard disk drive (HDD), e.g. baseline popping (BLP), writer-induced instability, permanent magnet reversal instability, spiking noise, random telegraph noise and amplitude asymmetry of a signal [1-6]. Thus, it is apparent that the head instability can degrade the system performance significantly.

Generally, the head instability resulting from an electrostatic discharge effect primarily yields two disturbances, viz. an amplitude spike caused by some defects inside the head [4, 7] and an unstable baseline (UB) caused by dielectric breakdown in the head [8, 9]. This paper focuses only on the UB problem, which causes the amplitude of the readback signal to drop dramatically and vary around 0 volt for many bit periods, as illustrated in Figure 1. Note that the UB event in fact occurs randomly throughout the magnetic medium because it is caused by the read head. Specifically, the UB event will not always occur at the same location on the medium. In practice, the UB event can cause an error burst in the data detection process, which can easily exceed the correction capability of an error-correction code and thus result in a sector read failure and degrade the disk drive reliability. It is inevitable that the UB effect becomes worse as the recording density increases. Consequently, the UB detection method is essential in the testing process before assembling the HDDs in a clean room.

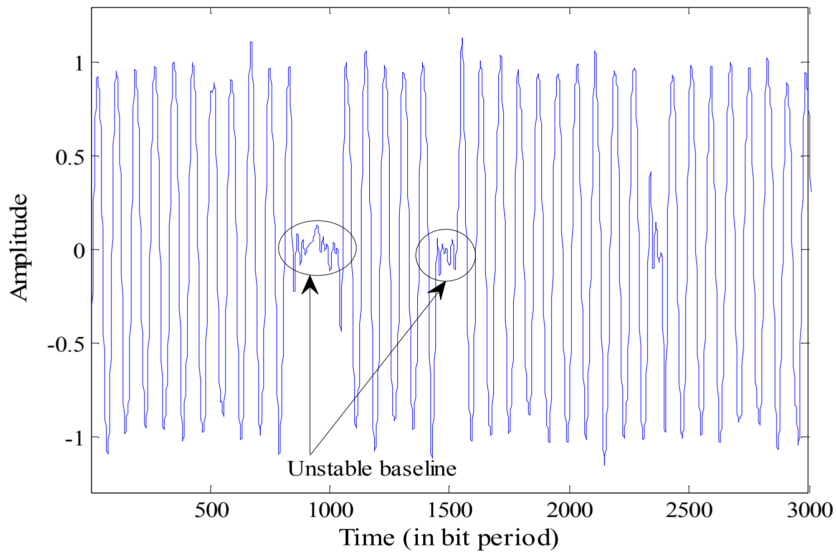

Figure 1. The UB-affected readback signal at SNR = 28 dB

To test whether the read head is stable, a square-wave signal of 2T or 4T pattern (T = bit period) depending on the write frequency and recording capacity, which corresponds to the binary sequence of [0 0 ... 1 1 0 0 1 1 ... 0 0] or [0 0 0 0 ... 1 1 1 1 0 0 0 0 1 1 1 1 ... 0 0 0 0] respectively, is written into the medium. Note that current high-density HDDs employ a 4T pattern signal to test the performance of the read head. Then the read head reads these specific data and sends the readback signal to a testing engineer to check if it looks normal or not. If the amplitude in some portions of the readback signal suddenly drops and varies around 0 volt for several bit periods, the read head is declared unstable. In other words, the read head contains the UB event. When this occurs, that read head will be discarded from the manufacturing process. Therefore, an efficient UB detection method is necessary for the testing process to ensure that all commercial HDDs do not have any defective read head inside.

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Sometimes the read head may start having some defects after a customer uses the HDD for a while. When this happens, the read head starts to malfunction and thus creates some UB events in the readback signal. This problem is unwanted because it renders the customer unable to retrieve some important data from the HDD. Again, an efficient UB detection method is needed in this case because if we can detect the UB event and it is not too severe, we might be able to recover the data by re-reading the data sector or forcing the iterative decoding to increase the number of error-correction iterations.

Several studies related to the detection and the root cause of head instability have appeared in the literature. For example, Chen et al. [1] investigated the types of head instability in perpendicular magnetic recording, which include BLP, writer-induced instability, permanent magnet reversal instability, spiking noise and random telegraph noise. Yang [4] presented a method to restore the head stability by automatically applying a bias shock current to the head according to the information received from a thermal asperity detection method. Zafer [5] introduced a method to detect BLP during servo reads by passing the readback signal through a digital filter and then computing the absolute value of the resulting signal before feeding it to a threshold detector. Song and Madden [6] presented a technique to correct the BLP event in the readback signal during acquisition mode. Li et al. [8] proposed the employment of a track average amplitude technique and a threshold detector to detect both the BLP and the UB. Finally, Du [9] introduced a method to detect the UB and the baseline shift in the readback signal by using an adjustable filter, which is placed between a pre-amplifier circuit and a servo circuit.

In this paper we propose three simple methods to detect the UB event caused by an unstable read head that loses an insulator state. Specifically, this type of read head will cause the amplitude of the readback signal to drop considerably and fluctuate around 0 volt for many bit periods. Also, we suggest some possible solutions to solve the UB problem in perpendicular magnetic recording systems.

CHANNEL MODEL

To investigate the performance of the proposed UB detection methods, we use the simulated signal generated from a channel model shown in Figure 2. A data input sequence $a_k \in \{-1, 1\}$ with bit period T is filtered by an ideal differentiator $(1-D)/2$, where D is the unit delay operator, to form a transition sequence $d_k \in \{-1, 0, 1\}$, when $d_k = \pm 1$ corresponds to a positive or a negative transition, and $d_k = 0$ corresponds to the absence of a transition. Hence the transition sequence d_k passes through a magnetic recording channel represented by $g(t)$. The transition response $g(t)$ for perpendicular recording is given [10] by:

$$g(t) = \operatorname{erf}\left(\frac{2t\sqrt{\ln 2}}{\mathrm{PW}_{50}}\right) \tag{1}$$

where erf(.) is an error function and PW_{50} determines the width of the derivation of $g(t)$ at half of its maximum. In the context of magnetic recording, a normalised recording density is defined as ND = PW_{50}/T.

The UB-affected readback signal, $y(t)$, can be expressed as:

$$y(t) = \sum_k d_k g(t-kT) + n(t) + u(t) \tag{2}$$

where $n(t)$ is additive white Gaussian noise with two-side power spectral density $N_0/2$, and $u(t)$ represents the UB signal. Specifically, to simulate the signal $y(t)$, we assume that there is no

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transition (i.e. $d_k = 0$ for many bit periods kT's) during the UB event. Then the UB-affected readback signal $y(t)$ is filtered by a seventh-order Butterworth lowpass filter and is sampled at time kT, assuming perfect synchronisation. Here, the sampler output y_k is sent to the UB detection block to determine if the readback $y(t)$ contains the UB event, where Z in Figure 2 is a UB indicator such that $Z = 1$ means the presence of UB and $Z = 0$ means its absence. Then the sequence x_k is further processed by an equaliser and the Viterbi detector [11] to output the most likely input sequence a_k.

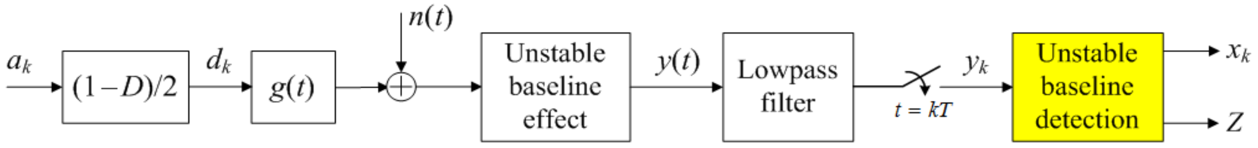

Figure 2. A perpendicular recording channel model with UB effect

UNSTABLE BASELINE DETECTION ALGORITHMS

Based on an averaging filter and the sequence $\{y_k\}$, three simple methods are proposed to detect the UB event. Each can be explained as follows.

Method 1

This method makes use of an envelope detector, as demonstrated in Figure 3. The received sequence $\{y_k\}$ is sent to the envelope detector, which attempts to detect the envelope of $\{y_k\}$, to obtain a sequence $\{p_k\}$. Note that the sequence $\{p_k\}$ comprises two components, namely an upper enveloped signal u_k and a lower enveloped signal l_k, as depicted in Figure 4.

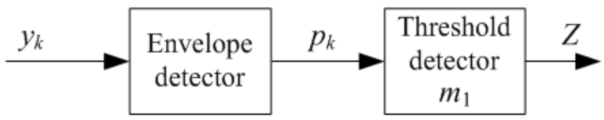

Figure 3. Method 1 for UB detection

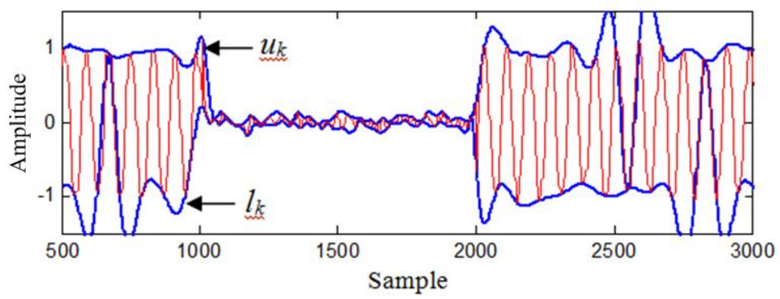

Figure 4. The upper (u_k) and lower (l_k) enveloped signals for Method 1

To detect the UB event, the signals u_k and l_k are used to compare with the threshold value m_1. Specifically, the UB is detected if there exists the signal at time kT that results in $u_k < m_1$ and $|\, l_k \,| < m_1$, where $|\, l_k \,|$ is the absolute value of l_k. This method is simple but it is sensitive to the

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amplitude fluctuation. Therefore, the method is in practice good for a 4T-patterned signal, not a random signal (or an actual user data).

Method 2

The second UB detection method is displayed in Figure 5. Here, the sequence $\{y_k\}$ is first passed through an absolute operator to obtain a signal $r_k = | y_k |$. Then the signal r_k is sent to an averaging filter with a window length of L samples to obtain the signal q_k [12] according to:

$$q_k = \frac{1}{L} \sum_{i=k-\beta}^{k+\beta} r_i \tag{3}$$

where $\beta = (L-1)/2$. Similarly, to detect the UB, the signal q_k is compared with the threshold value m_2. Specifically, the UB is detected if $q_k < m_2$. Figure 6 illustrates an example of the signals obtained from Method 2. In general, this method is more robust to signal fluctuation than Method 1 and also has low complexity.

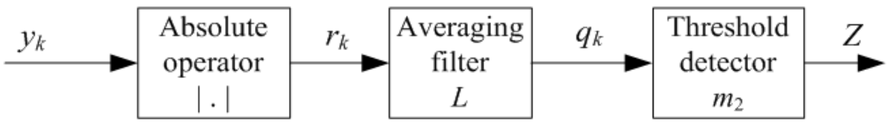

Figure 5. Method 2 for UB detection

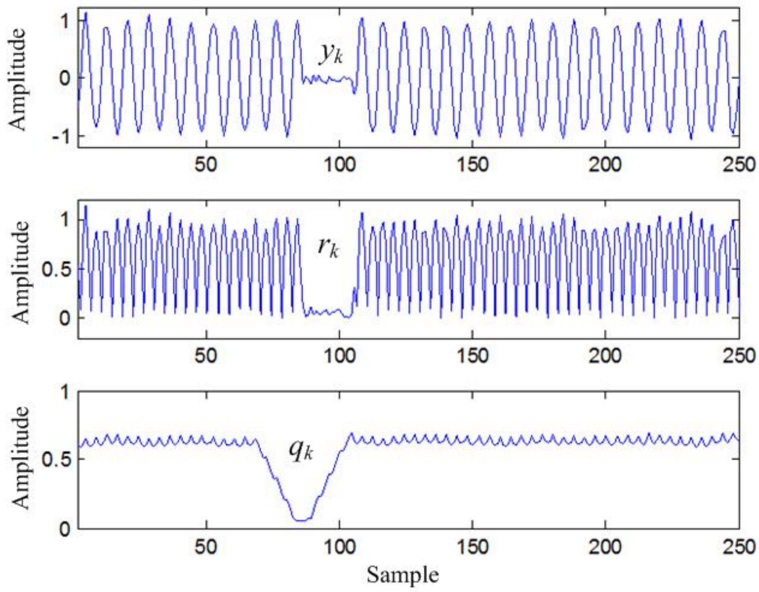

Figure 6. Example of signals $\{y_k, r_k, q_k\}$ from Method 2

Method 3

To improve the performance of Method 2, we propose Method 3 as depicted in Figure 7. Again, the signal y_k is passed through an absolute operator to obtain a signal $r_k = | y_k |$. Thus, the amplitude of the signal r_k at specific portions will be enlarged to ease the UB detection process. Specifically, the adjusted signal z_k is given by

$$z_k = \begin{cases} A + \Delta, & r_k > m_3 \\ r_k, & \text{else} \end{cases}, \tag{4}$$

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where Δ is a large number (e.g. 10), A = 1 is assumed to be the peak amplitude of the UB-unaffected readback signal, and m_3 is a threshold value. After that the adjusted signal z_k is fed to an averaging filter with a window length of L samples to obtain the signal q_k according to (3).

Similarly, to detect the UB, the signal q_k is compared with the threshold value m_4. Specifically, the UB is detected if $q_k < m_4$ for three consecutive samples so as to make it more robust to false alarm. Note that with enlarged signal, Method 3 can now utilise a smaller L than that in Method 2 for averaging the signal. Figure 8 shows an example of the signals obtained from Method 3.

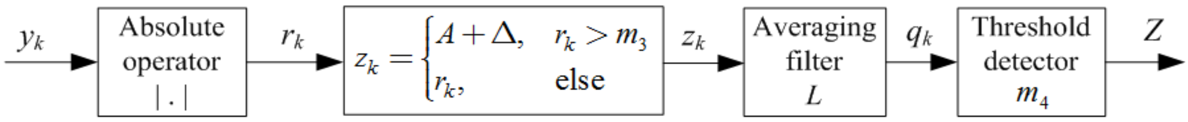

Figure 7. Method 3 for UB detection

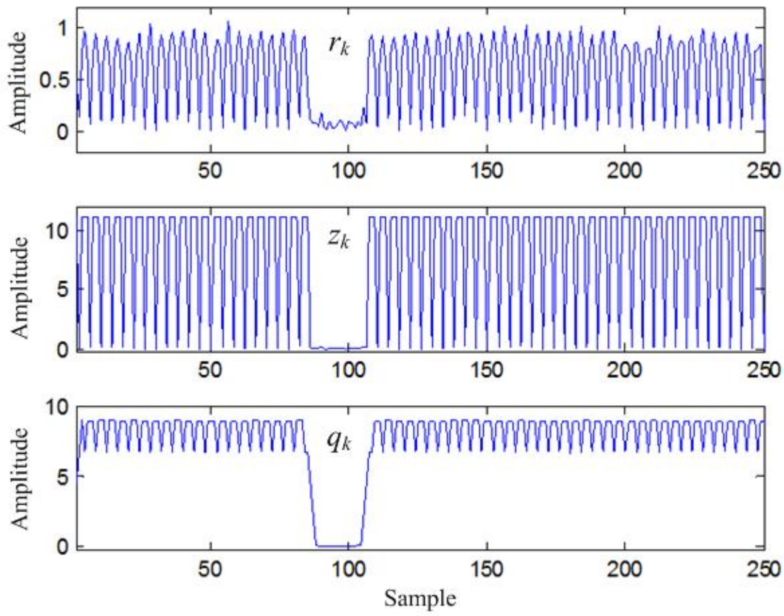

Figure 8. Example of the signals $\{r_k, z_k, q_k\}$ from Method 3

NUMERICAL RESULTS

Consider the perpendicular recording channel in Figure 2 at ND = 2 and signal-to-noise ratio (SNR) = 21 dB, where bit-error rate (BER) = 10^{-5} at the output of the sequence detector when the readback signal has no UB event. Here, SNR = $10\log_{10}(E_i/N_0)$ in decibel (dB), where E_i is the energy of the channel impulse response. We use the partial-response target $H(D) = 1 + 2D + D^2$ at ND = 2 [13]. The 11-tap finite impulse response equaliser is designed based on a minimum mean-squared error approach [14]. We also assume that each data sector contains one UB event starting at the 100th bit.

Figure 9 illustrates the system performance in terms of BER at the output of the Viterbi detector for different UB events. Each BER point was computed using as many 4096-bit data sectors as needed to collect 1000 error bits. Because each data sector contains one UB event, we

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call the BER as 'UB-given BER.' It is apparent that the UB event degrades the system performance, especially when it covers several bit durations.

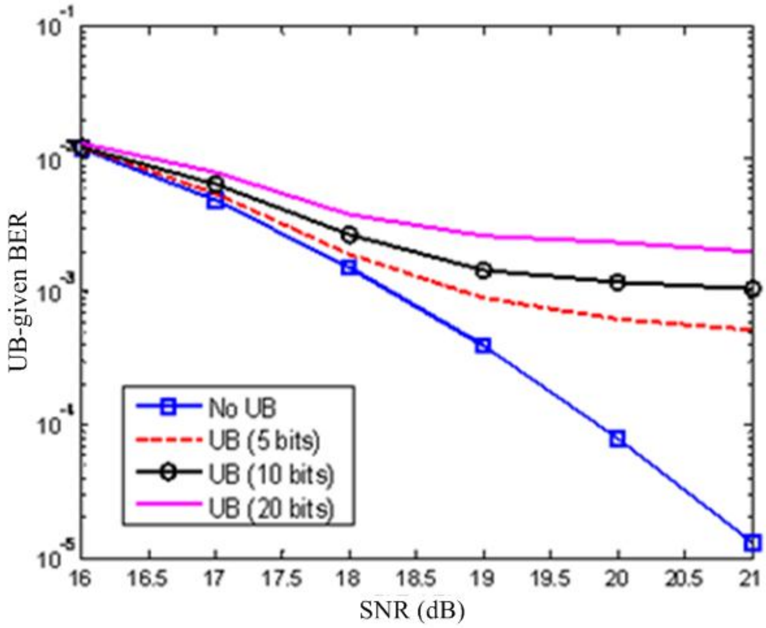

Figure 9. BER performance for different lengths of UB event

Here, we compare the performance of the three proposed UB detection methods, all of which are designed to detect the UB event only, without finding its exact location. Two cases are considered, viz. when the data input is 4T pattern (used in the testing process) and when the data input is random (after a customer uses the HDD). The parameters utilised for each method (optimised at ND = 2 and SNR = 21 dB by maximising the percentage of detection and minimising the percentage of false alarm) are the following:

- Method 1: $m_1 = 0.15$ for both random data and 4T-pattern data
- Method 2: $\{L = 31, m_2 = 0.12\}$ for random data, and $\{L = 15, m_2 = 0.5\}$ for 4T-pattern data
- Method 3: $\{L = 21, \Delta = 10, m_3 = 0.3, m_4 = 2\}$ for random data, and $\{L = 5, \Delta = 10, m_3 = 0.3, m_4 = 3\}$ for 4T-pattern data

4T-Pattern Data

Practically, when the read head is in the testing process to check whether it is defective, the 4T-pattern data is usually written into a disk and read out by the tested read head. If there are some portions of the readback signal that have very small amplitude for several bit periods (see Figure 1 for example), the UB event is identified.

Figure 10 compares the performance of each method by plotting the percentage of detection as a function of the number of missing bits (in the UB event). For each performance point, we ran 1000 data sectors (each with one UB event). Then we counted the number of data sectors for which the proposed methods can detect the UB event correctly and computed the percentage of detection. Clearly, Method 3 can detect the UB event better than the others, followed by Method 2. Both Method 2 and Method 3 performed well and could detect the UB event that contained at least four missing bits. On the other hand, Method 1 could only detect the UB event efficiently when the number of missing bits was greater than 10 bits.

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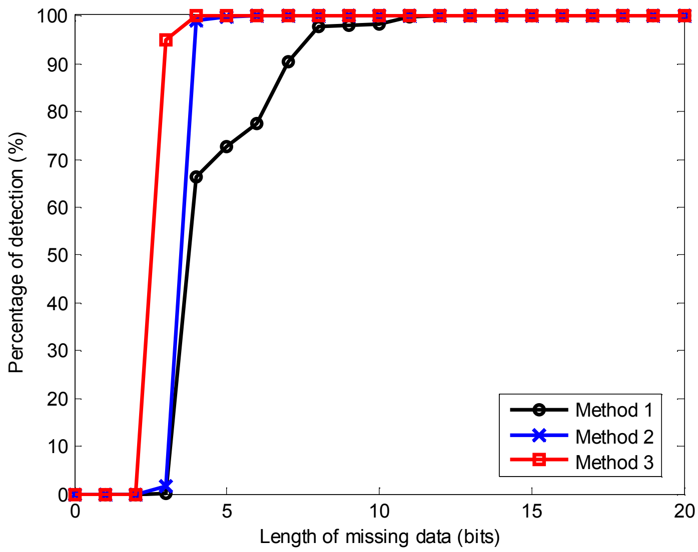

Figure 10. Performance comparison between UB detection methods based on 4*T*-pattern data

Random Data

When the UB event occurs in random data $\{a_k\}$, it is difficult to notice its existence in the readback signal, especially when the number of missing bits in the UB event is small as illustrated in Figure 11. With random data, we found that (not shown here) Method 1 does not work (even if the number of missing bits is large) because it relies merely on the enveloped signals u_k and l_k.

Figure 11 compares the performance of Method 2 and Method 3. Apparently, Method 3 can detect the presence of the UB event better than Method 2. Nonetheless, both methods can detect the UB event efficiently when the number of missing bits in the UB event is greater than 30 bits.

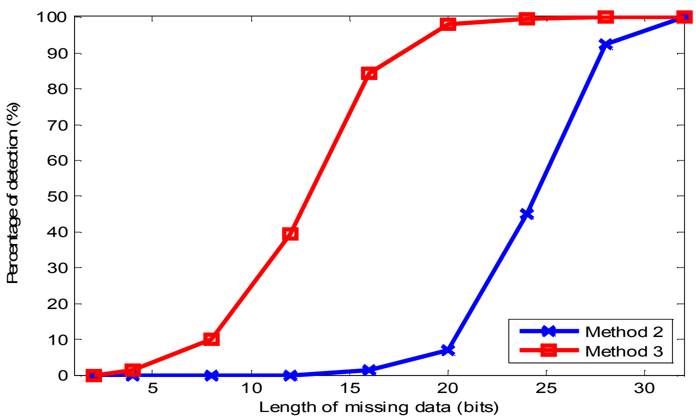

Figure 11. Performance comparison of Method 2 and Method 3 based on random data

CONCLUSIONS

Instability of the magneto-resistive head can cause a spike baseline or a UB, depending on the type of the defective head. This paper focuses on the UB and proposes three simple methods to detect it. Results show that all methods can detect the UB event for 4*T*-pattern data that is employed during the testing process, with Method 3 performing best. However, for random data, Method 1 can no longer work, and Method 3 performs better than Method 2. It should be pointed out that in

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real hard disk drives, the UB detection can be further used to determine the number of error-control iterations for correcting the lost bits. Additionally, it can also be employed to indicate whether the drive is needed to re-read the data sector that contains the UB event.

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