Experimental Studies of Noise Autocorrelation in Thin Film Media

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Abstract—Noise voltage autocorrelation in thin film media has been experimentally studied in the time domain. Unlike a spectral measurement, the time domain noise autocorrelation function provides a good characterization of non-stationary noise that is particularly useful for thin film media. A new measurement technique is developed to eliminate the noise due to the lack of noise-free timing reference. An empirical eigenfunction expansion is applied to the measured noise autocorrelation matrix to identify possible physical mechanisms for the noise modes and eliminate alignment jitter. The noise autocorrelation function is reconstructed by using only the leading noise modes.

INTRODUCTION

Noise in magnetic recording always accompanies recorded signals as in any other information system. To recover the signal, it is critical to understand and characterize the noise. The importance of noise correlation arises as new detection methods, such as PRML, are utilized, because the joint detection probability between two sample points is a crucial input to these types of detection methods. In thin film media, noise characterization and correlation are more challenging because the medium noise is signal dependent [1] and concentrated in the region where the magnetization vanishes [2] [3]. Consequently, to provide a good characterization, noise must be measured in the presence of a transition. Conventionally measured noise spectra, as the Fourier Transform of the noise correlation function, provides very useful information, especially when the noise is stationary. However, since the spectral measurements utilize time domain averaged noise properties, the detailed relation between noise and magnetization is lost.

The time domain noise autocorrelation function provides a good characterization of non-stationary noise. Some commonly used medium characteristics, such as total noise power and position jitter are consequences of this correlation function [4]. Direct time domain noise correlation measurements were achieved by Tang using a pulse delay trigger technique [5] [6]. In this paper a new time domain measurement technique that does not require a special trigger is proposed. The method is applied to a standard thin film head/disk system. An empirical eigenfunction expansion is applied to the measured correlation function to identify the leading noise modes and eliminate the effect of inaccurate trigger.

THEORY AND MEASUREMENT TECHNIQUE

The nonstationary noise autocorrelation function is defined as:

\[ C(t_1,t_2) = \langle n(t_1) n(t_2) \rangle \]  

where \( t_1 \) and \( t_2 \) are fixed temporal points (sample points). The leading diagonal line of this matrix, where \( t_1 = t_2 \), represents the noise power at each time, \( \langle n \rangle \) is an ensemble average which is performed by summing over correlation functions for all collected noise waveforms, normalized by the total number of waveforms. \( n \) is the \( 5^{th} \) noise waveform in the presence of transitions (an isolated transition in this study). The noise waveform is the directly measured waveform subtracting the averaged waveform:

\[ n(t) = S_{\text{measured}}(t) - S_{\text{averaged}}(t) \]  

As shown in (1), noise correlation between any two temporal or spatial points can be determined given \( C \). Since the magnetization

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correlation function (without the misalignment) and the alignment jitter matrix (the second term in (3)). The validity of this approach is guaranteed by the fact that the alignment jitter can be determined by measuring the fluctuation of the separation of the two peaks. The two peaks are well separated, hence the noise at the two peaks are not correlated. In this case, the peak separation fluctuation equals the individual peak position fluctuation (the alignment jitter) times \( v_2 \). The nonstationary noise autocorrelation function, \( C \), can be determined by using (3) An alternative approach to remove the alignment jitter, i.e., subtracting the alignment jitter from the directly measured total jitter (determined by using eigenfunction expansion), is described in next section.

The experiment was performed on a disk test bed. A thin film head with a 0.7 \( \mu \)m gap was used. The thin film disk utilized was of \( H_e = 1226 \) Oe, \( M_r \beta = 4.14 \) memu/cm\(^2\). The noise floor of the amplifier used for both write and playback was 0.8 nV/Hz. The frequency response was flat up to 40 MHz. A Tektronix DSA 602A digital scope was used for waveform collection and the final data analysis was performed on an IBM PC. The entire track was DC bulk erased then written with a low frequency square wave noise in the DC head with a 0.7 Oe, \( 4.14 \) memu/cm\(^2\) alignment jitter (i.e., subtracting the alignment jitter from the directly measured total jitter (determined by using eigenfunction expansion), is described in next section.

The nonstationary noise autocorrelation function, \( C \), can be determined by directly using a workstation. A 200 \times 200 matrix was used. The leading eigenvalues and corresponding weights are given in Table 1. It is clear that only the few leading noise modes are relatively important and the leading three are shown in Fig. 4. The average pulse is also plotted in the same figure. From the eigenfunction shape, the first resembles closely the derivative of the isolated pulse. If this mode is interpreted as jitter, the amount of jitter (including alignment jitter) is determined from the eigenvalue. The alignment jitter, which was separately measured from the peak separation fluctuation, was then removed from the total jitter. Because the medium and alignment jitter are not correlated (due to well-separated pulses), the net jitter was determined by directly subtracting the alignment jitter from the total \( C_a \) jitter. The net jitter was 0.98\pm0.06 ns for this disk/head combination. Since the alignment only introduces a jitter (included in the first mode) and the noise modes are orthogonal to each other, the other noise modes are not altered by the subtraction of the isolation jitter. The second eigenfunction resembles a playback pulse. It peaks at the center and contains no node, characteristic of amplitude noise. The third noise mode also peaks at the center, but contain three nodes. The area of the third eigenfunction is very close to zero. This can be identified as transition width fluctuation. The eigenvalues for other noise modes are very small. Considering only the jitter, amplitude fluctuation and misalignment, the weights are 23\%, 66\%, and 11\%.

**Table 1**

<table>
<thead>
<tr>
<th>Eigenfunction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>...</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>1223.8</td>
<td>543.7</td>
<td>91.9</td>
<td>55.6</td>
<td>44.2</td>
<td>...</td>
<td>13.6</td>
</tr>
<tr>
<td>Weight(%)</td>
<td>55.6</td>
<td>24.7</td>
<td>4.2</td>
<td>2.5</td>
<td>2.0</td>
<td>...</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**EMPIRICAL EIGENFUNCTION EXPANSION**

It is desired to understand the noise mechanisms given the measured correlation function. An empirical eigenfunction expansion, also known as a Karhunen-Loeve expansion was used to identify the noise modes and then further possible corresponding mechanisms [7]. The principle of this expansion is: Given a matrix (correlation function), a set of orthogonal eigenfunctions is derived with corresponding eigenvalues. The weight of each eigenfunction (eigenvalue normalized to the sum of all eigenvalues) ranks the relative importance of the eigenfunction. The shape of the eigenfunction provides a possible physical meaning that is not guaranteed by the expansion.

The expansion was numerically applied to the correlation matrix \( C_a \) by using a workstation. A 200 \times 200 matrix was used. The leading eigenvalues and corresponding weights are given in Table 1. It is clear that only the few leading noise modes are relatively important and the leading three are shown in Fig. 4. The average pulse is also plotted in the same figure. From the eigenfunction shape, the first resembles closely the derivative of the isolated pulse. If this mode is interpreted as jitter, the amount of jitter (including alignment jitter) is determined from the eigenvalue. The alignment jitter, which was separately measured from the peak separation fluctuation, was then removed from the total jitter. Because the medium and alignment jitter are not correlated (due to well-separated pulses), the net jitter was determined by directly subtracting the alignment jitter from the total \( C_a \) jitter. The net jitter was 0.98\pm0.06 ns for this disk/head combination. Since the alignment only introduces a jitter (included in the first mode) and the noise modes are orthogonal to each other, the other noise modes are not altered by the subtraction of the isolation jitter. The second eigenfunction resembles a playback pulse. It peaks at the center and contains no node, characteristic of amplitude noise. The third noise mode also peaks at the center, but contain three nodes. The area of the third eigenfunction is very close to zero. This can be identified as transition width fluctuation. The eigenvalues for other noise modes are very small. Considering only the jitter, amplitude fluctuation and misalignment, the weights are 23\%, 66\%, and 11\%.
leading noise modes (4 and 5 may be reversed).

The alignment jitter, as long as it is deterministic, can be removed according to (3). But large alignment jitter buries the medium jitter that one intends to measure. A high sample rate is required for alignment proposal. Each waveform is shifted to line up its first peak. The alignment jitter, i.e. the peak position fluctuation, is a multiple of the timing interval between two neighboring sample points (inverse of the sample rate). Low sample rate, introduces a large statistical fluctuation in the alignment jitter and then causes inaccuracy of the measurement. One way to compensate a sample rate that is not sufficiently high is to interpolate each waveform before alignment. Statistical fluctuation in the alignment jitter measurement process due to the finite number waveforms used only affects the measured medium jitter (not other modes). A low noise floor, flat frequency response amplifier is crucial in this study. Lowpass filtering is also recommended.

Noise in the recording channel originates from the possible mechanical instability of the set-up and the micromagnetic behavior of the medium [4]. Therefore, the noise measured is not the medium noise alone. The head noise, the noise caused by head-medium spacing fluctuations, disk run-out and speed variation, etc., are included. The correlation function itself may not be physically composed of different modes. The empirical expansion provides a good characterization of the correlation function by decomposing the matrix into eigenfunctions, which can be effectively interpreted as jitter, amplitude fluctuation and transition width fluctuation, etc. from the shapes of their functionforms. The original correlation matrix can then be reconstructed by using few leading eigenfunctions (with assigned physical meanings). The empirical eigenfunction expansion forces the output eigenfunctions to be orthogonal. Therefore, the white electronic noise or some other high frequency noise may be decomposed and hence contribute to the leading noise modes. Because overall electronic noise is much lower than medium noise in the transition region and also is decomposed to all the eigenfunctions, these contributions are small.

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DISCUSSION

A new method of measuring nonstationary noise correlation is developed. The experimental procedure is: 1) DC erase medium and write a low frequency square wave; 2) Digitize waveforms shown in Fig. 1 at a high sample rate; 3) Align the first peaks of all waveforms, calculate the average and the noise correlation function (include the alignment jitter) of the second pulses; 4) Apply the empirical eigenfunction expansion to the channel noise correlation function, identify jitter and the other noise modes from the eigenfunction shapes; 5) Measure the peak separation fluctuation and hence the alignment jitter, calculate the net jitter. 6) Reconstruct the correlation fluctuation by using only the few

CONCLUSION

A noise correlation measurement technique is developed and demonstrated as a simple and practical method to measure transition dependent noise. An empirical eigenfunction expansion is a promising tool to characterize the noise mechanisms and remove alignment jitter. Jitter, amplitude fluctuation and transition width fluctuation are identified as the leading noise modes. The corresponding weights vary for different media. The noise correlation function can also be reconstructed (filtered) by using the few leading eigenfunctions.

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REFERENCES