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Practical Equalizer for a Perpendicular Magnetic Disk

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***Abstract*—We have developed a readback equalizer for a perpendicular magnetic disk with a commercial anisotropic magnetoresistive head for use with a PR4ML read channel with 8–9 coding. The transfer function of the perpendicular magnetic disk, derived by Fourier analysis, has a phase lag of 90° from that of the longitudinal magnetic disk. We defined the parameters of the equalizer by simulation. The equalized readback signal nearly satisfied Nyquist's first criterion. Using resistor-capacitor circuits that correspond to the simulated function, we obtained a byte-error rate of below 10^{-7}. Comparing the effect of incorporating PR4 or PR1 as part of the equalizer, we observed that PR4 gave a lower bit-error rate than PR1. Thus, PR4 is an effective detection method for a perpendicular magnetic disk. It is suitable not only for longitudinal magnetic disks, but also for perpendicular magnetic disks.**

***Index Terms*—Byte-error rate (BER), 8–9 coding, equalizer, Fourier analysis, magnetoresistive (MR) head, perpendicular magnetic disk, phase, PR4ML, pseudodifferential circuit, RC circuit.**

I. Introduction

HIGH-QUALITY video contents are needed for digital broadcasts and the recording system for such broadcasts must have both a high transfer rate and a large capacity. The perpendicular magnetic disk is thought to be suitable for high-density recording [1] and is expected to perform an important role in digital media. Despite the potential advantage of this storage medium, there are no practical readback equalizers for perpendicular magnetic disks with a magnetoresistive (MR) head. One approach is to use a simple readback equalizer with a conventional PR4ML [PR4 : PR(1, 0, −1)] LSI for longitudinal magnetic disks (Fig. 1). If the PR4ML LSI is a suitable equalizer, then it may allow perpendicular magnetic disks to be used as a practical recording system that offers advantages over a longitudinal magnetic disk [2]. We have developed a practical readback equalizer for a perpendicular magnetic disk using a commercial anisotropic magnetoresistive (AMR) head (merged ring inductive head for writing) and the PR4ML read channel. It consists of three simple cascading resistor–capacitor (RC) pseudodifferential circuits, and provides a low byte-error rate (BER). We also compared the effect of PR4ML with differential circuits for a perpendicular magnetic disk with PR1ML [PR1 : PR(1, 1)].

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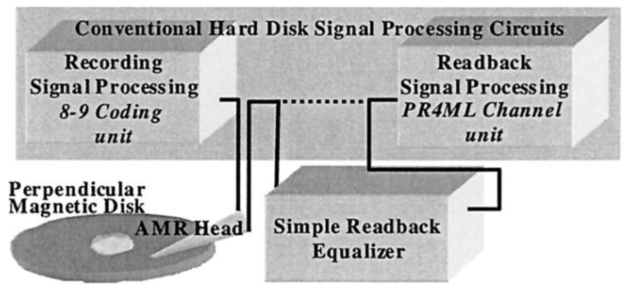

Fig. 1. Insertion location of the equalizer.

TABLE I
EXPERIMENTAL CONDITIONS

Perpendicular magnetic disk		AMR head	
Recording layer (Co-Cr-Ta)		Write track width	3.0 [μm]
Thickness	0.05 [μm]	Write gap length	0.35 [μm]
M_s	400 [emu/cc]	Read track width	2.3 [μm]
$H_c \perp$	2.4-3.0 [kOe]	Read gap length	0.27 [μm]
Underlayer (Co-Zr-Nb)		Sense current	10.0 [mA]
Thickness	0.6 [μm]	Write current	8.0 [mA]
B_s	12000 [Gauss]	**Mechanical conditions**	
μ	600-800	Apparatus	Spinstand
Pinning layer (Co-Sm)		Writing velocity	6.75 [m/s]
Thickness	0.15 [μm]	Flying height	0.04 [μm]

II. Design of Equalizer

A. Analysis of an Isolated Waveform

It is important to analyze head/disk transmission characteristics when designing an equalizer [3]. A readback signal with a pseudorandom pattern is a suitable way to analyze transmission characteristics for equalizing signals correctly. However, we have selected a rectangular pulse signal instead of a pseudorandom pattern as the recording signal for the channel analysis because it is simple to generate and provides a step signal that corresponds to a quarter of a cycle in the pulse and has a continuous spectrum. Table I shows the experimental conditions. The perpendicular magnetic disk [4] was evaluated at a writing velocity corresponding to 242 kfci at 32 MHz. 32 MHz corresponds to a half standard television signal rate [5]. The transmission characteristics of perpendicular and longitudinal disks are considered to be linear [3].

Generally, the reverse function gives optimized equalizing characteristics if the transfer function is linear. The calculation was performed as follows:

$$f_o(t) = h(t) * f_i(t) \tag{1}$$

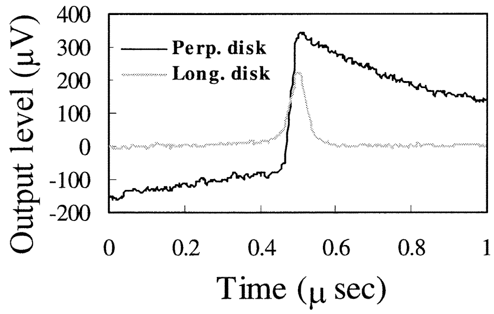

Fig. 2. Readback isolated waveforms of Perp.disk and Long.disk.

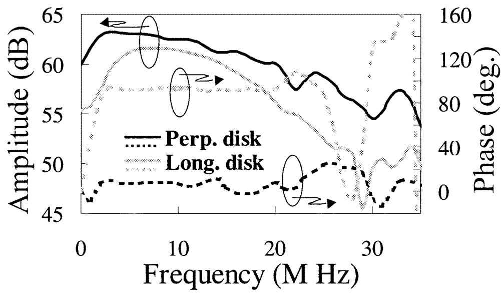

Fig. 3. Transfer functions of perpendicular and longitudinal magnetic disk.

where $f_i(t)$ and $f_o(t)$ are input and output signals, respectively, and $h(t)$ is a linear impulse response and $*$ means convolution. The Fourier transformed equation (1) is

$$F_o(\omega) = H(\omega) \cdot F_i(\omega) \tag{2}$$

where $H(\omega)$ is the transfer function and consists of amplitude term $|H(\omega)|$ and phase term $\theta(\omega)$. Hence, $H(\omega)$ also indicates

$$H(\omega) = |H(\omega)| e^{j\theta(\omega)}. \tag{3}$$

Readback-isolated waveforms of perpendicular magnetic disk and longitudinal magnetic disk (H_c : 2400 Oe, B_r : 100 μm) are shown in Fig. 2. The isolated waveform of a perpendicular magnetic disk was apparent as a rectangular waveform. The sag shape apparent in this isolated waveform is caused by the characteristic of the high-pass filter of the preamplifier.

The transfer functions of perpendicular magnetic disk and longitudinal magnetic disk obtained from each isolated waveform by writing step signals are shown in Fig. 3. These transfer functions are similar, differing mainly in high frequency regions. The phase characteristics of the perpendicular magnetic disk have a phase lag of about 90° compared with the longitudinal magnetic disk. Therefore, it is considered that the equalizer for a perpendicular magnetic disk must have a phase advance 90° circuit for use with a conventional read channel LSI. The phase rotation of the longitudinal magnetic disk observed at 28 MHz is not due to a readback signal but is the result of noise and can, therefore, be ignored.

B. Simulation for Equalizing

Cascading RC pseudodifferential circuits (Fig. 4) are potentially suitable for an equalizer as they are phase advance 90° circuits. An equalizer with buffer amplifiers in front of each RC pseudodifferential circuit and a transversal filter, as shown in Fig. 5, was simulated using the following circuit transfer function:

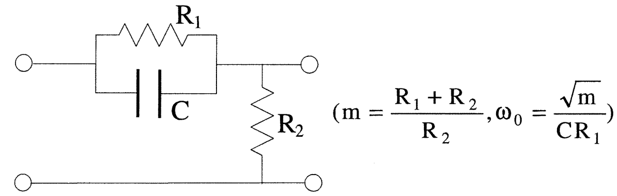

Fig. 4. Pseudodifferential circuit.

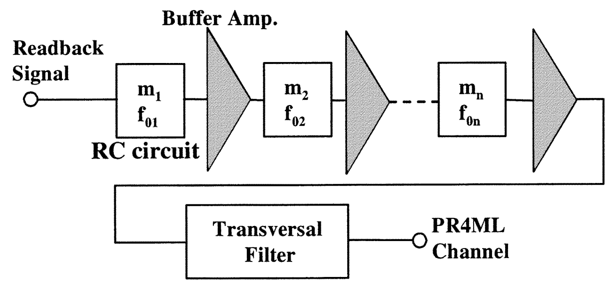

Fig. 5. Block diagram of simulation.

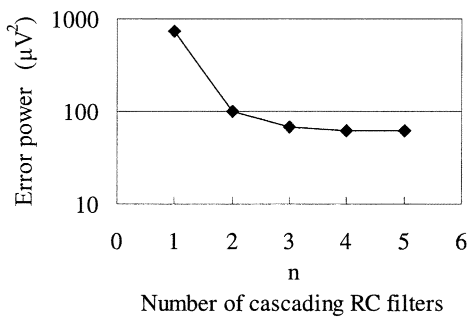

Fig. 6. Error power between Nyquist waveform and the equalized signal through cascading RC filters (simulation).

$$H(\omega) = \frac{1/\sqrt{m} + j(\omega/\omega_0)}{\sqrt{m} + j(\omega/\omega_0)} \tag{4}$$

where m is an emphasis factor and ω_0 is the angle frequency of an inflection point.

Equalization to the Nyquist waveform is equivalent to giving the readback waveform a phase advance of 90°. In this simulation, the error power between the equalized signal and the Nyquist waveform was calculated for 55 samples near the region where the energy was concentrated as the stages of the RC filters were increased and the m and ω_0 values were changed. The Nyquist rate was set at 64 Mb/s and rolloff coefficient was 0.9. It must be noted that m is below six in practice, because of limitations of the values of resistors and capacitors generally used.

Similar error powers were obtained at each of the three stages of the RC filters, as shown in Fig. 6. The m and ω_0 values were $m_n = 5.46, 3.52, 2.74, \omega_{0n}/2\pi = f_{0n} = 0.82, 5.31, 6.80$ MHz, respectively. This equalized waveform is close to the Nyquist waveform shown in Fig. 7.

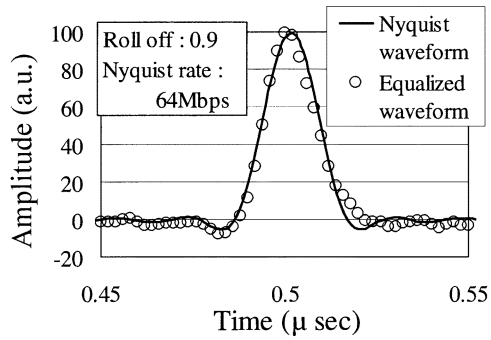

Fig. 7. Equalized waveform in the simulation with the Nyquist waveform.

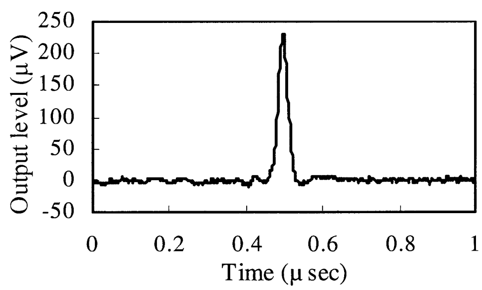

Fig. 8. Equalized waveform using the pseudodifferential circuits.

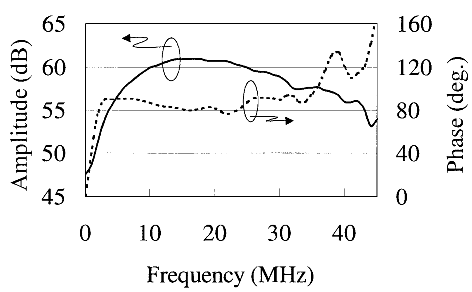

Fig. 9. Transfer function of equalized waveform using the pseudodifferential circuit.

III. READ/WRITE EXPERIMENTS USING A NEW EQUALIZER

The read/write characteristics of a perpendicular magnetic disk with an AMR head were investigated using the equalizer shown in Fig. 5. The equalized waveform through the pseudodifferential circuits is shown in Fig. 8. This waveform was equalized so that it was identical to the waveform of longitudinal magnetic disk. The amplitude and phase characteristics are shown in Fig. 9. The amplitude characteristic, after equalization was almost the same as the characteristics prior to equalization. The phase characteristics of the equalized waveform are advanced 90° and virtually flat in the applied frequency region. Spectra of equalized and nonequalized readback signals at 32 MHz (corresponding to 305-kfci linear recording density) are shown in Fig. 10. The noise spectra of the equalized signal are lower in the low frequency region and very similar to the high frequency region compared with the spectra of nonequalized signals.

The BER was investigated at a fixed data rate of 57 Mb/s using 8–9 coding and a PR4ML channel with the equalizer, while changing the linear recording density. A data rate of 57 Mb/s corresponds to a code rate of 64 Mb/s. This code rate equals the Nyquist rate selected when simulating the equalizer.

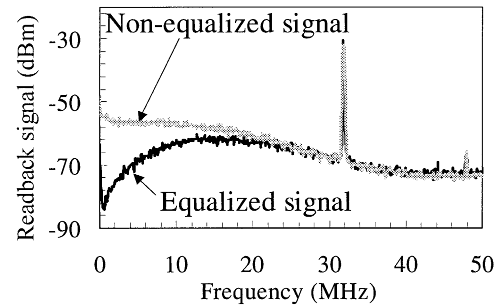

Fig. 10. Spectra of readback signals at 32 MHz.

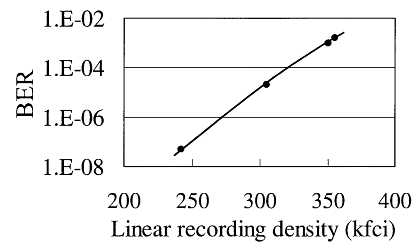

Fig. 11. Relationship of linear recording density to BER.

The BER was below 10^{-7} at 242 kfci and near 10^{-5} at 305 kfci, as shown in Fig. 11. This BER is considered to be sufficiently low for practical use. The writing velocity used in the read/write experiment, 242 kfci, was the same as that of the analyzed waveform used when designing this equalizer. Based on these findings, the equalizer, which consists of simple RC circuits, is suitable for a perpendicular magnetic disk. Thus, the perpendicular magnetic disk, with a commercial AMR head, can be used at a linear recording density of about 305 kfci by inserting this equalizer. The equalized signal of the perpendicular magnetic disk has a peak of noise spectrum at 16 MHz, as shown in Fig. 10. A lower BER will be obtained when the equalizer is used to make this noise lower.

IV. COMPARISON WITH PR1

The effect of PR4 with a differential circuit for a perpendicular magnetic disk was compared with PR1.

Since the number of detection levels is the same in both PR1 and PR4 channels, the PR1 channel is chosen over the PR2 [6] in our simulation. Because the equalization for PR1 does not have to advance the phase of a readback signal from a perpendicular magnetic disk, a readback signal was detected without the RC filters.

The amplitude characteristics of an equalized signal for PR1 and an ideal PR1 are shown in Fig. 12.

An equalized signal for PR1 was simulated using only a transversal filter from a readback-isolated waveform of a perpendicular magnetic disk (Fig. 2). The definition of signal-to-noise ratio in Fig. 12 is the following. S is a power at 25 MHz. N is a root-mean-square noise power integrated at over 0–50 MHz bandwidth. The amplitude characteristics at 4–24 MHz were almost the same. However, the amplitude of the equalized signal at 30 MHz was 8.1 dB higher than the ideal. In comparison, the

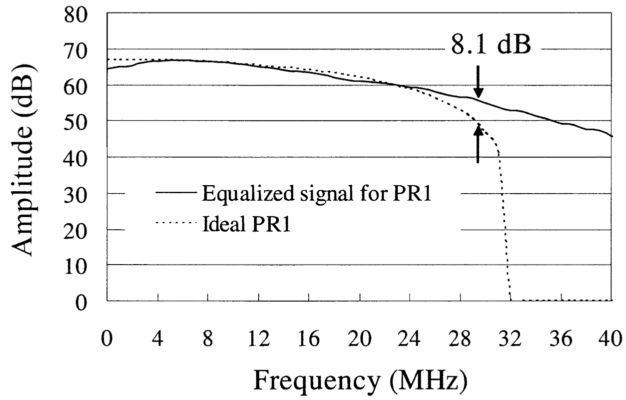

Fig. 12. Amplitude characteristics of PR1.

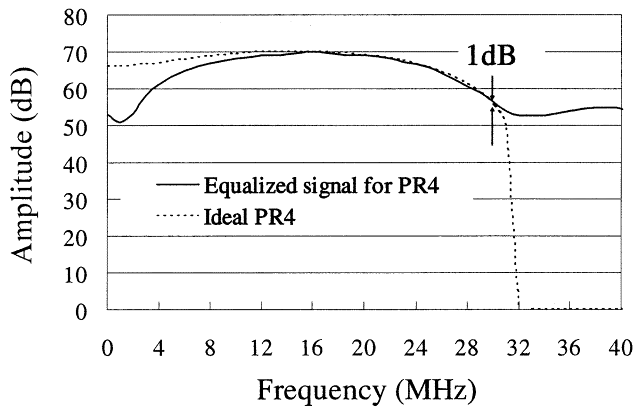

Fig. 13. Amplitude characteristics of PR4.

amplitude characteristics of an equalized signal recorded using the equalizer illustrated in Fig. 7 for PR4 are shown in Fig. 13.

The equalized signal for PR4 was also simulated using RC filters and utilizing the same readback-isolated waveform as those shown in Fig. 13. The amplitude characteristics were different than those of the optimum signal at frequencies below 14 MHz, whereas the characteristics of the equalized signal corresponded to those of the ideal signal in the 14–30 MHz frequency range.

A pseudorandom signal was then used for the simulation modeling a filter with the characteristics of the readback-isolated waveform generated by the perpendicular magnetic disk shown in Fig. 2. This signal corresponded to a readback random signal at the linear density of 242 kfci. This linear density was derived from both a writing velocity of 6.75 m/s and a code rate of 64 Mb/s at simulation. The bit-error rate (bER) achieved with this random signal was measured using a software ML (Viterbi) decoder. The bER obtained with the PR4ML decoder was lower than that of the PR1ML decoder as shown in Fig. 14. The difference in magnitude at more than 30 MHz between the equalized signal for PR1 and the ideal PR1 (Fig. 12) was larger than the difference between that of PR4 and the ideal PR4 shown in Fig. 13. This difference at higher frequency gives a large effect in the bER for the PR1 because the effect is to boost noise. The phase characteristics of this perpendicular magnetic disk are not exactly 0° (shown in Fig. 3), there being a phase advance of about 10°. Despite this, a phase advance circuit, such as this pseudodifferential circuit, is an effective filter for a perpendicular magnetic disk. PR4ML is a suitable detection method for the perpendicular magnetic disk.

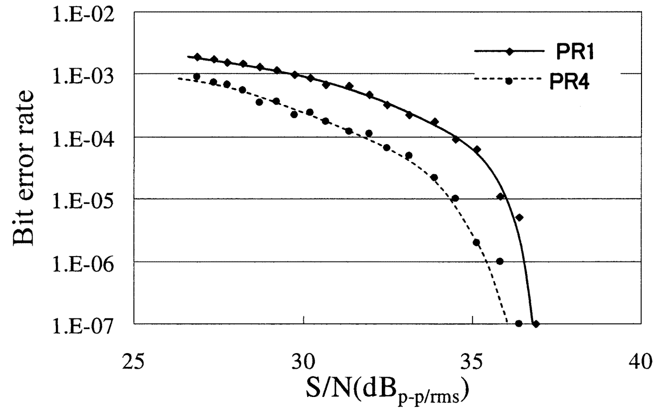

Fig. 14. Relationship between signal-to-noise ratio and bER.

V. Conclusion

An equalizer for a perpendicular magnetic disk using the PR4ML read channel was designed by analyzing a transfer function of an isolated readback waveform. It was found that the use of three cascading RC pseudodifferential circuits is suitable for a perpendicular magnetic disk; first, because these circuits are very simple, and second, because the equalized waveform is close to the Nyquist waveform. Inserting this equalizer in front of the PR4ML read channel and using a perpendicular magnetic disk with a commercial AMR head, achieved a BER of less than 10^{-7} at 242 kfci and approximately 10^{-5} at 305 kfci. These results suggest that the RC pseudodifferential circuit is a practical equalizer for perpendicular magnetic recording with an AMR head. The lower bER obtained with the PR4 shows that PR4ML is an effective detection method for a perpendicular magnetic disk.

These results are expected at higher linear density recording on a perpendicular magnetic disk using PR4ML.

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