Write equalization in high-linear-density magnetic recording

by Richard C. Schneider

For many years, equalization has been used on the read side of a magnetic-recording channel to obtain a desired signal shape at the detector. Compensation on the write side has, for the most part, been limited to moving transition locations to offset read-signal peak shifts. This paper presents a new method of equalization on the write side through the addition of pulses at strategic locations on the write waveform. The resulting write current continues to be a two-level signal, so ac bias is not required. A linear transfer function can be derived for these write equalizers. This enables the recording-channel designer to partition the equalization more optimally between the write and read sides. The principal benefit of write equalization is that the read-flux-amplitude differences between high and low densities are significantly reduced. This permits maximum use of the linear operating region of the magnetoresistive read head. By providing high-frequency boosts on the write side, write equalization can reduce high-frequency noises at the read detector. Test results of channel linearity, as well as read signal waveshapes, are presented.

Introduction

High-density magnetic-recording systems often use electronic equalization to extend the useful limits of the recording channel. When digital saturation recording is employed, this equalization is usually performed on the read side [1–4]. Compensation on the write side has been, for the most part, limited to time-shifting the write-current transitions to offset read-signal peak shift. Some ad hoc work has added extra write-current pulses to shape the resulting read signal [5–10]. However, the optimum pulse locations had to be determined experimentally, and there was no assurance that the process was linear.

This paper describes a method of write equalization that is achieved by adding write-current pulses and analytically optimizing the pulse locations. Pulses are added so that the write current continues to be a two-level signal. Saturation recording is used, and ac bias is not required. It is also shown that this process is linear and that the write-equalizer transfer function can be calculated straightforwardly. The fact that the write equalizer is linear enables the designer to partition the equalization between the write and read sides. If the write equalizer were not linear, its transfer function would vary with each data pattern. Therefore, it would not be possible to design a fixed read equalizer. As used in the IBM 3480 Magnetic Tape Subsystem, write equalization produces two unique benefits: First, it reduces the flux-amplitude differences between high and low densities, allowing maximum use of the linear operating region of the magnetoresistive read head. Second, it provides significant high-frequency boosts on the write side. This avoids the signal-to-noise-ratio degradation that would occur if the

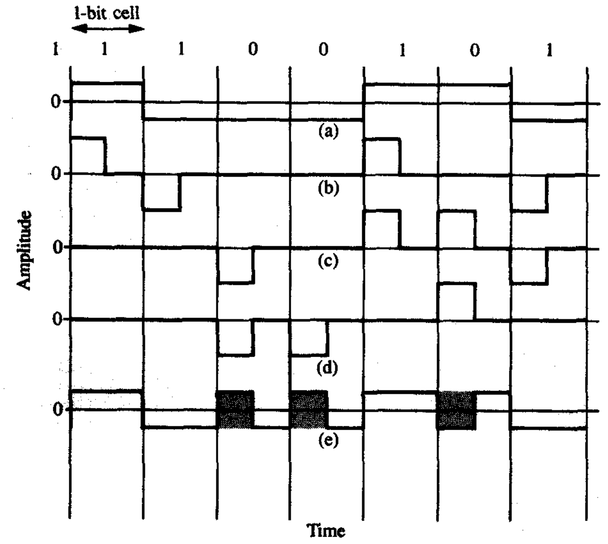

Figure 1

Write-equalizer filter waveforms: (a) conventional NRZI data; (b) to (d) intermediate outputs; (e) final filter output.

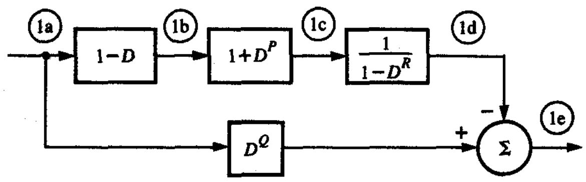

Figure 2

Block diagram of the write equalizer's digital filter.

same high-frequency boosts were to be performed with the 3480 read equalizer.

In the following sections of this paper, it is first demonstrated that this method of write equalization can be described as a linear digital filter. Once this concept is understood, the designer can calculate the magnitude and phase changes of the transfer function as functions of the location of the added pulses. The paper concentrates on the addition of a single pulse for each zero of the run-length code; in general, however, any number of additional pulses may be used.

Subsequent sections show how write equalization is implemented through the use of timing and block diagrams, and how a linear transfer function is derived from the block diagrams. The relationship between the write-equalizer frequency response and the position of the added pulses is also explored. The section on test results presents data indicating the linearity of the overall recording channel. The waveshapes of the resulting read signals are also given in this section. The conclusions summarize the major features and advantages of the 3480 write equalizer.

Description of write equalization

In conventional NRZI (nonreturn-to-zero IBM), transitions are made at the start of a bit cell for a one, and a zero is the absence of a transition [11]. This section shows that a write-equalized waveform can be obtained by passing NRZI data through a digital filter that adds pulses to the NRZI signal. This demonstrates that the write-equalization process is linear and that a linear transfer function can be derived. Three examples are given: the first uses the 3480 filter parameters; the second uses a change in the position of the added pulses; and the third uses a change in the width of the added pulses.

Refer to the timing diagram of **Figure 1**. These waveforms represent the outputs of the digital filter blocks shown in **Figure 2**, where D is a delay of half a bit period, $Q = 0$, and $P = R = 2$. The waveform of Fig. 1(a) represents conventional NRZI write current. The desired write-equalized waveform shown in Fig. 1(e) is the final output of the filter of Fig. 2. The other waveforms [Fig. 1(b), (c), (d)] are the output of the intermediate blocks of Fig. 2, as indicated in the block diagram. Although other filter block combinations will produce the same output waveform of Fig. 1(e), these different combinations will all have the same transfer function. The important concept is that the write equalizer is linear. It is left to the circuit designer to choose the most cost-effective construction.

Figure 1 illustrates the special case in which the D^Q term of Fig. 2 equals 1, which means that there is no delay for this block. The effect of the filter of Fig. 2 is to add pulses to the NRZI waveform. In the example shown in Fig. 1, the pulses are a half-bit wide and a single pulse is added for each zero. In this special case only, the write-equalized waveform appears as a frequency-modulation (FM) waveform, where the zeros rather than the ones represent the high frequency. As is subsequently shown in the section on test results, the high frequency is beyond the bandpass of the recording channel and is not used for the recovery of clock information. Clock information is obtained by using a run-length-limited code.

The added pulses are shown shaded in Fig. 1(e). Straightforward modifications to this case include changing the pulse position ($D^Q \neq 1$), changing the pulse width, or both. It is also possible to add more than one narrower pulse for each zero. This can be accomplished by adding parallel pulse-generating legs to the basic filter of Fig. 2. Care must be taken to ensure that a two-level write current is preserved. All of these modifications have the effect of altering the write-equalizer transfer function, as is shown in the following section. It is also shown that this addition of pulses boosts the frequencies above the all-ones frequency and attenuates the frequencies below the all-ones frequency. For the case in which the added pulses are a half-bit wide, the resulting equalized-write-current waveform is dc balanced with a spectral null at zero frequency. Dc-balanced write current is required when the write current is coupled through a transformer to the write head, as in a rotary-head system.

Equalizer transfer function

The transfer function of the write equalizer is easily derived from the block diagrams of Fig. 2. Consider the case illustrated in the timing diagram of Fig. 1, where D is a half-bit wide, $P = 2$, $Q = 0$, and $R = 2$. Combining the individual terms from each block, we obtain

$$G_1(D) = 1 - \frac{(1 - D)(1 + D^2)}{1 - D^2}, \quad (1)$$

which simplifies to

$$G_1(D) = \frac{D(1 - D)}{1 + D}. \quad (2)$$

The first D in the numerator can be dropped, because it represents a constant time delay. The delay does not affect the write-equalizer magnitude response or the shape of the write current or read signals. This yields

$$G_1(D) = \frac{1 - D}{1 + D}. \quad (3)$$

To get the transfer function in the frequency domain, $e^{-j\omega T/2}$ is substituted for D, where T is the time of a single-bit period. This yields

$$G_1(\omega) = \frac{1 - e^{-j\omega T/2}}{1 + e^{-j\omega T/2}}. \quad (4)$$

After some trigonometric manipulations, we obtain

$$G_1(\omega) = j \tan (\omega T/4). \quad (5)$$

In write equalization, pulses are added for each zero. The transfer function can be modified by changing the pulse width, pulse position, or number of pulses. Consider the case in which the added half-bit-wide pulses are centered between the normal NRZI transitions. This is equivalent to $Q = 1/2$ and $P = R = 2$ in the block diagram of Fig. 2. The following transfer function can be derived:

$$G_2(\omega) = \frac{2 \sin \omega T/8 \sin 3\omega T/8}{\cos \omega T/4}. \quad (6)$$

As in Eq. (3), a constant time-delay term has been dropped in the derivation of Eq. (6).

Now consider the case in which D is a quarter-bit wide, $Q = 0$, and $P = R = 4$. The pulses added to the NRZI signal are a quarter-bit wide. The leading edge of each pulse occurs at the same time as the leading edge of the pulses shown in Fig. 1(e). As in the first two examples, the following transfer function can be derived:

$$G_3(\omega) = \frac{1 - \cos \omega T/2}{2 \cos \omega T/4} + \frac{j(\tan \omega T/8 \cos \omega T/2)}{(2 \cos \omega T/4)}. \quad (7)$$

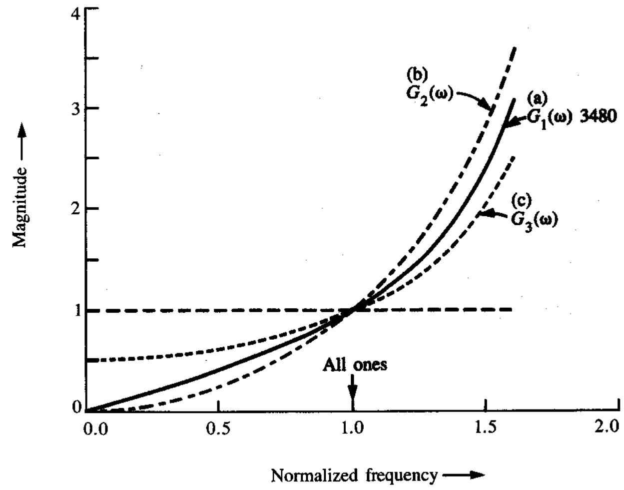

Figure 3

Three write-equalizer transfer functions: (a) 3480 method; (b) centered-pulse position; (c) narrow-pulse filter.

The magnitude responses of these three transfer functions are shown in **Figure 3**. The three functions attenuate frequencies below the all-ones frequency and amplify frequencies above all-ones. The transfer function of Eq. (5) also provides a 90° phase shift. This is somewhat analogous to differentiation [6, 7]. The transfer function of Eq. (6) has 0° phase at all frequencies. Thus, only a high-frequency boost is provided [5, 8, 9]. Phase that varies with frequency can be provided by choosing an intermediate pulse position or width, as in Eq. (7). The phase of the transfer function $G_3(\omega)$ is shown in **Figure 4**. Other variations of both magnitude and phase are obtainable by varying the pulse position, pulse width, or number of added pulses. Note that if the pulse is a half-bit wide, then there is a null at dc, as illustrated in Fig. 3. The narrower pulse width of $G_3(\omega)$ results in a nonzero response at dc and a reduction in the amount of boost above the all-ones frequency. In all cases, there is unity gain at the all-ones frequency, because no extra pulses are added in the all-ones pattern.

The 3480 tape drive uses the type of equalizer described by the timing diagram of Fig. 1 and by Eq. (5). The position and width of this pulse require a clock that runs at only twice the data frequency. Other pulse positions and widths

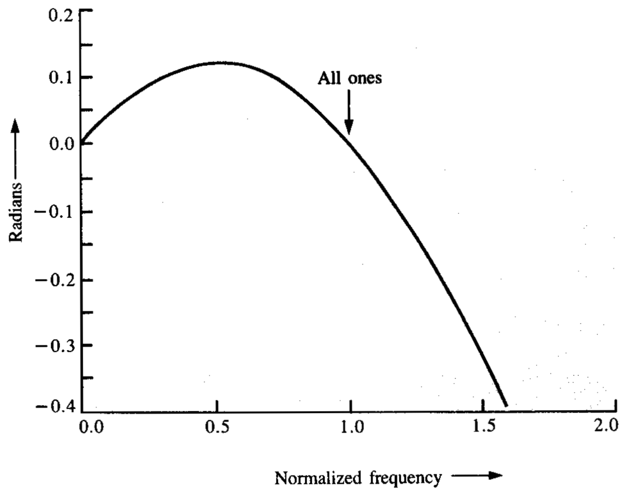

Figure 4

Phase response of narrow-pulse transfer function, $G_3(\omega)$.

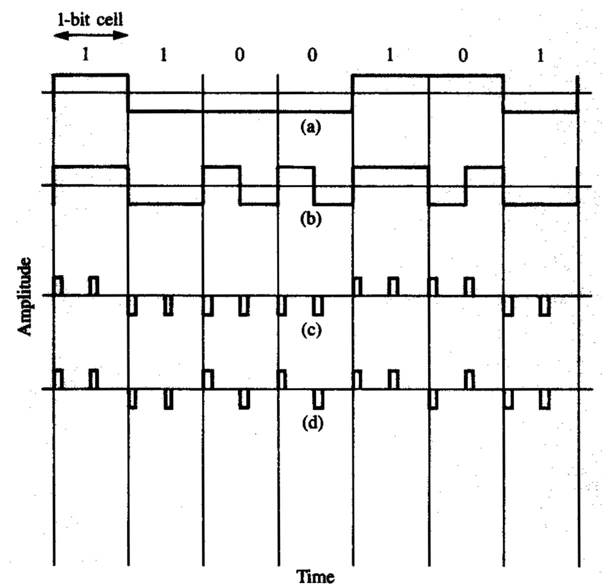

Figure 5

Write current waveforms: (a) continuous NRZI; (b) continuous write-equalized; (c) pulsed NRZI; (d) pulsed write-equalized.

require higher clock frequencies. This general type of equalization is ideally suited to the thin-film write head and the magnetoresistive read head used in the 3480 tape drive. The low inductance of the thin-film write head allows the use of narrow added pulses. As shown in the following section, the resulting write current produces a read signal of more uniform amplitude. This permits maximum use of the linear region of the magnetoresistive read element.

The write-equalized-current waveforms shown so far in this paper are continuous. When a thin-film write head with a small number of turns is used, the current may be pulsed to reduce power dissipation. This can be done by sampling the continuous waveform of Fig. 1(e) twice each bit period. The resulting write current has an RZ (return to zero) appearance, as shown in **Figure 5**. As long as the flux bubble produced by each pulse spans several bit periods, the resultant recorded flux is essentially identical to that produced by a continuous current. In the remainder of this paper, the continuous convention is understood. The reader should recognize that a pulsed write current can be used for all the write equalizers described, provided that the flux-bubble dimensions are correct.

Test results

The block diagram of Fig. 2 and the transfer functions of Eqs. (5–7) demonstrate that the write-equalizer circuit itself is a linear digital filter. It is equally important to determine whether the entire recording channel is linear. In the case of the digital magnetic-recording channel, a restricted sense of linearity is used. A channel is defined as linear when

$$G_j(\omega) = R_j(\omega)/W_j(\omega) \simeq G_c(\omega) \qquad \text{for all } j, \tag{8}$$

where $W_j(\omega)$ is the Fourier transform of the write current for an arbitrary data sequence, $R_j(\omega)$ is the transform of the resulting read signal, and $G_j(\omega)$ is the calculated transfer function [12].

When a write equalizer with transfer function $WEQ(\omega)$ is used, it is important that the overall measured transfer function, $G_T(\omega)$, obey the following equation:

$$G_T(\omega) \simeq WEQ(\omega) \cdot G_c(\omega), \tag{9}$$

where $G_c(\omega)$ is the measured transfer function of the recording channel without a write equalizer. Refer to **Figure 6**, where $\hat{G}_c(\omega)$ is defined to be the recording-channel transfer function when write-equalized current is used. If

$$\hat{G}_c(\omega) \simeq G_c(\omega), \tag{10}$$

it implies that the recording channel remains essentially unchanged by the use of the write equalization. It also implies that Eq. (9) is true. The following test was performed. An estimate of the overall transfer function $G_T(\omega)$ was made from

$$\hat{G}_T(\omega) = WEQ(\omega) \cdot G_c(\omega), \tag{11}$$

where $G_c(\omega)$ was measured and $WEQ(\omega)$ is the $G_1(\omega)$ obtained in Eq. (5). Next, the actual overall transfer function $G_T(\omega)$ was measured, and $G_T(\omega)$ and $\hat{G}_T(\omega)$ were compared. The estimated and measured transfer function magnitude and phase showed excellent agreement. As an example, the

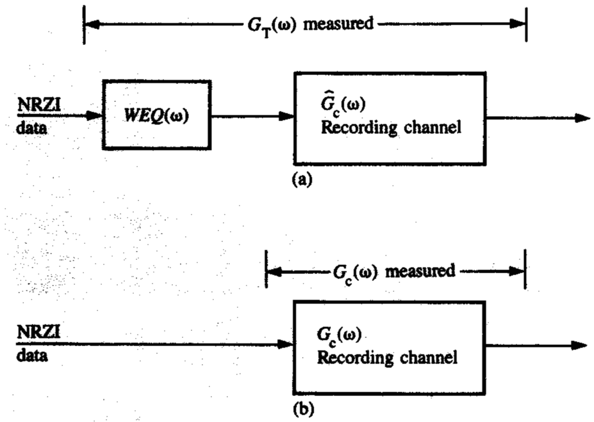

Figure 6

Transfer function measurements: (a) with write equalizer; (b) without write equalizer.

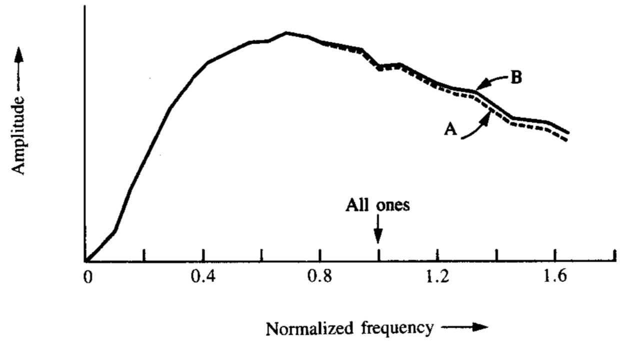

Figure 7

Transfer function comparison: Curve A, $G_T(\omega)$ measured; Curve B, $\hat{G}_T(\omega)$ calculated.

magnitude comparison is shown in **Figure 7**. This demonstrates that the recording channel remains essentially unchanged and linear when write equalization is used. **Figure 8** compares typical read signals, with and without write equalization. The normally high-amplitude, low-density signals have been reduced by write equalization. The design of the magnetoresistive read element can now be optimized for the all-ones data without read-signal nonlinearity caused by low-density signals. It is also seen that the read signal has the appearance of differentiated read signals (except for a delay), as mentioned in the previous section. A significant amount of high-frequency boost is provided by the write equalizer. Therefore, less high-frequency boost is required in the read equalizer, resulting in reduced high-frequency noise at the detector. The write-equalized read signal of Fig. 8(d) shows that the high frequency for zeros is beyond the recording-channel bandwidth. Therefore, these transitions are not used for clocking as with conventional FM. The 3480 uses a (0,3) run-length code [13] to ensure that no more than three consecutive zeros can appear in the recorded data.

Summary and conclusions

The 3480 write equalizer belongs to a class of write equalizers in which pulses are added to the NRZI data for each zero to be recorded. Linear transfer functions can be derived for all equalizers in this class. The magnitude and phase of the transfer function can be varied by changing the added pulse position, the pulse width, or the number of added pulses for each zero. It has been shown that the overall recording channel remains linear. This enables the designer to partition the needed equalization between the write and read sides of the recording channel.

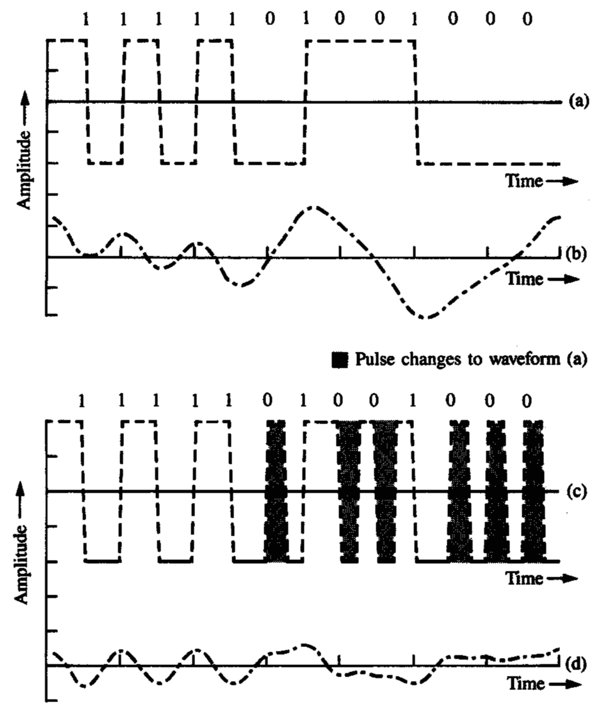

Figure 8

Comparison of write and read waveforms: (a) conventional write current; (b) conventional read signal; (c) write-equalized current; (d) write-equalized read signal.

This type of write equalizer is ideally suited for the 3480 read/write head. The thin-film write head has a low inductance that allows the use of the narrow-equalized current pulses. The resulting read signal has a uniform amplitude that permits maximum use of the linear region of the magnetoresistive read element. By placing high-frequency boosts on the write side, the amount of high-frequency noise at the detector is reduced.

Acknowledgments

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References

1. H. M. Sierra, "Increased Digital Magnetic Recording Readback Resolution by Means of a Linear Passive Network," *IBM J. Res. Develop.* **7**, No. 1, 22–33 (January 1963).
2. G. V. Jacoby, "Signal Equalization in Digital Magnetic Recording," *IEEE Trans. Magnetics* **MAG-11**, No. 5, 302–305 (September 1975).
3. R. C. Schneider, "An Improved Pulse Slimming Method for Magnetic Recording," *IEEE Trans. Magnetics* **MAG-11**, No. 5, 1240–1241 (September 1975).
4. C. S. Chi, "Characterization and Spectral Equalization for High-Density Disk Recording," *IEEE Trans. Magnetics* **MAG-15**, 1447–1449 (November 1979).
5. R. C. Schneider, "Modified Double Frequency Encoding," *IBM Tech. Disclosure Bull.* **8**, No. 11, 1475 (April 1966).
6. S. C. Chao, "Binary Code Magnetic Recording System," U.S. Patent 3,277,454, October 1966.
7. R. F. Heidecker, "Predifferentiated Recording," U.S. Patent 3,603,942, September 1971.
8. M. I. Behr and N. S. Blessum, "Technique for Reducing Effects of Pulse Crowding in Magnetic Recording," *IEEE Trans. Magnetics* **MAG-8**, No. 5, 608–611 (September 1972).
9. R. C. Schneider, "Phase Shift Reducing Digital Signal Recording Having No DC Component," U.S. Patent 3,855,616, December 1974.
10. D. H. Veillard, "Compact Spectrum Recording, a New Binary Process Maximizing the Use of a Recording Channel," *IEEE Trans. Magnetics* **MAG-20**, No. 5, 891–893 (September 1984).
11. B. E. Phelps, "Magnetic Recording Method," U.S. Patent 2,774,646, 1956.
12. M. K. Haynes, "Experimental Determination of the Loss and Phase Transfer Functions of a Magnetic Recording Channel," *IEEE Trans. Magnetics* **MAG-13**, 1284–1286 (September 1977).
13. P. A. Franaszek, "Sequence-State Methods for Run-Length-Limited Coding," *IBM J. Res. Develop.* **14**, No. 4, 376–383 (July 1970).

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