F. E. Talke
R. C. Tseng

Effect of Submicrometer Transducer Spacing on the Readback Signal in Saturation Recording

Abstract: Experimental results for frequency response and halfpulse width of digital recording signals have been obtained for submicrometer transducer spacings, for the case of a flexible disk flying in close proximity to a rigidly mounted conventional ferrite recording head. Using optical flying heights rather than an "effective spacing," together with a modification of the Williams-Comstock write-process slope criterion, we have obtained excellent agreement between experimental results and theoretical predictions. This suggests that the notion of effective spacing can be avoided.

Introduction

In a recent paper [1], the authors investigated the dependence of the readback signal on the thickness of a particulate magnetic medium and on read transducer spacing for disk file systems using saturation recording. For the ranges of transducer spacing and thickness of medium investigated, general agreement with theoretical predictions was found for peak-signal amplitude and half-pulse width of isolated pulses. Increasing deviations from the theoretical curves seemed to occur as the transducer spacing decreased to 1.25 μm, the lower end of the flying height range.

Discrepancies between theory and experiment have also been found by other authors [2–7], especially under conditions of very close spacings between transducer and tape. To achieve agreement between experimental and theoretical data, Eldridge [2] assumed an "effective" head-tape spacing of 2 μm under contact recording conditions. The same effective spacing of 2 μm for contact recording was also used by Bonyhard, Davies, and Middleton [3] in calculating pulse amplitude and half-pulse width of digital signals on thin metallic tape. A somewhat smaller "effective contact spacing" of 0.5 μm to 0.75 μm was later suggested by Middleton [4], the former value being identical to that found by Teer [5] for contact recording. Effective spacings of the order of 0.5 μm were also introduced for sine wave recording for "in-contact" situations [6, 7].

The need for relatively large effective spacings for actual in-contact situations is surprising. Attempts for justification have been made on grounds of surface roughness effects, nonmagnetic layers on the head surface due to machining and wear [8], or magnetic dead layers on the surface of the medium [9]. On the other hand, it is well known that even in in-contact situations a small air film may exist at the transducer-medium interface, contributing perhaps substantially to the effective spacing. In fact, since it is quite likely that a thin air film may have been present at the head-medium interface in most of these investigations, the question arises: How well do different magnetic recording theories predict the experimental data if one knows accurately the physical head-medium spacing and if one uses this latter value rather than an effective spacing?

It is interesting that Potter and Schmulian [10] and Comstock and Williams [11], in the case of recording on a rigid disk, observed agreement between theory and experiment without recourse to effective spacing. Since rigid disks lend themselves much more readily to spacing measurements, we may conjecture that accurate flying height data for flexible media would, perhaps, also allow better correlation between theory and experiment.

The reliable measurement of extremely small physical spacings between head and flexible medium is difficult to realize because of dynamic effects at the interface in conventional tape drives. In this study we avoid these difficulties by considering a commercially available, oxide coated, flexible Mylar* disk that flies over a stationary, rigidly mounted transducer. Using special head adjustment fixtures and white light interferometric techniques [1, 12], we measured actual physical spacings in the submicrometer spacing region. After comparing our experimental data for frequency response and half-pulse width with the predictions of the simple theories, we observed varying degrees of agreement if we used the actual physical spacing. This, then, suggests that perhaps the notion of effective spacing can be avoided.

*Trademark, E. I. duPont de Nemours Company.

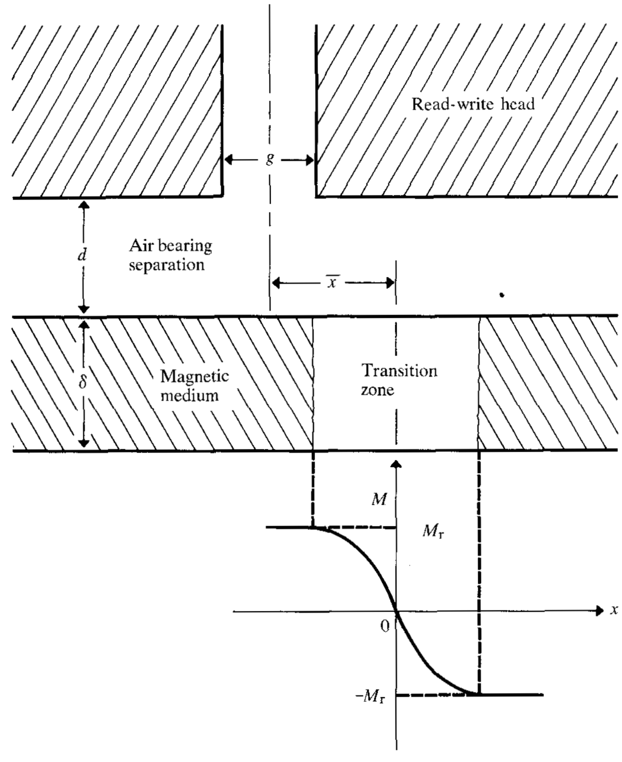

Figure 1 Configuration of the interface between the recording head and the recording medium. The lower diagram shows the magnetization transition zone.

Theoretical considerations

The main objective of the simple magnetic recording theories is to predict the pulse waveform due to an isolated transition and to calculate the frequency response at high packing densities by superposition of such isolated pulses. With the assumptions of a) unity medium magnetization and infinite transducer permeability, b) purely longitudinal magnetization of constant magnitude across the medium, c) infinite track width, and d) independence of the read and write process, it was shown by Speliotis and Morrison [13] that the read signal $e(\bar{x})$ of a transducer having a finite gap width (Fig. 1) due to an arctangent magnetization transition is a function of the flying height d, the medium thickness δ, the gap width g, and the magnetic transition parameter a.

Since g, δ, and d are related to the physical dimensions of the head-tape interface, the only parameter through which the recording process influences $e(\bar{x})$ is the transition parameter a. Thus, depending on the physical approximations made in modeling the recording process, one obtains different estimates for a. In particular, for the most idealized case of a perfect step transition we find $a = 0$. This case is physically unrealistic, because large demagnetization fields within the medium will broaden any step change in magnetization. Assuming that the maximum demagnetization field within the media equals the medium coercivity H_c, Potter [14] has derived the following expression for a in the demagnetization limit:

$$a = \frac{\delta}{4}\left(\operatorname{cosec}\frac{H_c}{8M_r} - 1\right), \quad (1)$$

where M_r is the remanent magnetization of the medium. If one disregards the effects of demagnetization and considers the effects of the head field gradient on the medium magnetization, the following estimate for a is obtained [1, 15, 16]:

$$a = \frac{2(1 - S^*)}{\pi}\left(d + \frac{\delta}{2}\right), \quad (2)$$

where S^* denotes the coercive squareness ratio of the linearized hysteresis loop. It is apparent that the value of a that exists in the medium is equal to or greater than the larger of the two values predicted by Eqs. (2) or (3). However, the neglect of either the effect of the head field gradient or of demagnetization on a is somewhat unsatisfactory.

Recently, a more complete analysis of the write process was carried out by Williams and Comstock [17], in which both the finite gradient of the head field and the effects of demagnetization resulting from the transition are considered for thin media with nonsquare hysteresis loops. Extending their analysis to the case of thick media, we have obtained the following expression for the modified Williams-Comstock transition parameter:

$$a = \left[\frac{a_1}{2r} - \frac{\delta}{4}\right] + \left\{\left(\frac{a_1}{2r} - \frac{\delta}{4}\right)^2 + \left(\frac{\delta}{2} + 2\pi\delta\chi\right)\frac{a_1}{r}\right\}^{\frac{1}{2}}, \quad (3)$$

where

$$\frac{a_1}{r} = \frac{y(1 - S^*)}{\pi Q} - \frac{\delta}{4r} + \left\{\left[\frac{y(1 - S^*)}{\pi Q} - \frac{\delta}{4r}\right]^2 + \frac{\delta y}{rQ}\left[\frac{4M_r}{H_c} + \frac{1 - S^*}{\pi}\right]\right\}^{\frac{1}{2}},$$

$$y = [d(d + \delta)]^{\frac{1}{2}},$$

$$r = 1 - \chi(1 - S^*)H_c/M_r,$$

$$\chi \approx \tfrac{1}{4}\frac{M_r}{H_c}, \text{ and}$$

Q is a function of y/g, which can be approximated by $Q \approx 0.866 - 0.216 \exp - [(5/3)(y/g)]$.

We note from Eq. (3) that for $\delta/a_1 \ll 1$ and $\delta/a \ll 1$, the result of Williams and Comstock [17] is recovered.

In addition to the analytical expression in Eqs. (1), (2), and (3), predictions for a have been obtained using harmonic analysis [18] or iterative methods [19]. These investigations, however, go beyond the scope of the simple theories and are not considered in this note.

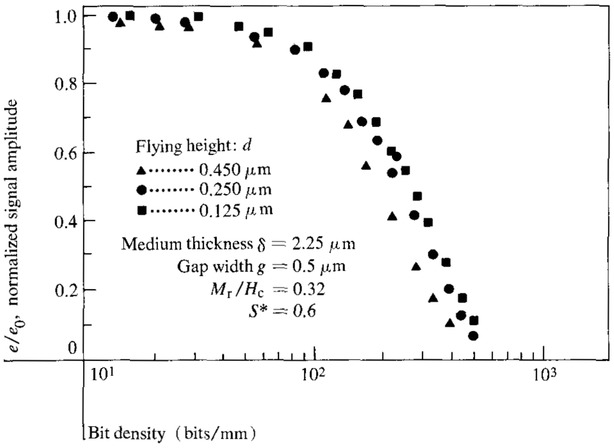

Figure 2 Typical experimental results for normalized readback signal as a function of bit density. $H_c = 2.39 \times 10^4$ A/m (300 Oe).

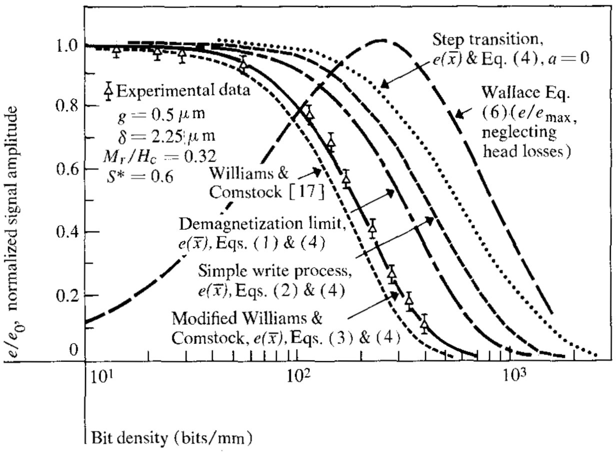

Figure 3 Comparisons of experimental and theoretical frequency response for two different magnetic media at separate flying heights. $H_c = 2.39 \times 10^4$ A/m, $d = 0.45$ μm.

In order to predict the frequency response of a recording system, linear superposition of isolated pulses may be applied [20, 21], i.e.,

$$e(\bar{x}=0) = \sum_{-\infty}^{+\infty} (-1)^n\, e(nb), \qquad (4)$$

where b is the distance between adjacent transitions. An alternative procedure for obtaining the frequency response is to superimpose a string of Lorentzian pulses [20] of the form

$$e(x) = 1\Big/\left[1 + \left(\frac{2x}{x_H}\right)^2\right], \qquad (5)$$

where x_H is the half-pulse width of the isolated pulse. Finally, in the case of sine wave recording, the classical analysis of Wallace [22] predicts

$$e(t) = k'(1 - e^{-2\pi\delta/\lambda})\, e^{-2\pi d/\lambda} \frac{\sin \pi g/\lambda}{\pi g/\lambda} \cos \omega t, \qquad (6)$$

where λ denotes the wavelength of the recorded signal, ω is 2π times the reproduced frequency, and k' is a system constant.

Experimental procedure

The flexible disk used in our experiment was mounted on a 25-mm diameter vertical shaft driven by a variable dc motor. A stationary Bernoulli-type base plate, adjustable in the axial direction, was used to stabilize the rotating disk relative to the base plate. The rigidly mounted magnetic head protruded through a small cutout in the base plate and could be positioned relative to the flexible disk by means of a micrometer adjustment. In addition to this vertical adjustment, special high resolution pitch and roll adjustments on the head mount permitted change in the relative position of the air bearing on the head.

To measure the head-tape spacing, we first mounted a clear Mylar disk on the disk drive. Precautions were taken to ensure that the thickness and stiffness properties of the clear Mylar disk were nearly identical to those of the Mylar disk containing the magnetic medium. Thereafter, head roll, pitch, and protrusion were adjusted until stable white light interference fringes [1, 12] could be observed between the head and the clear Mylar disk. Finally, the clear Mylar disk was replaced by one containing the magnetic coating, thus allowing the measurement of magnetic signals corresponding to the previously measured flying height.

For the heads used in the experiment, stable flying heights were achieved in the spacing region up to 0.5 μm. Flying heights above this spacing required flexible suspension rather than rigid mounting. The accuracy of the white light interferometric spacing measurement is approximately ±0.025 μm.

Comparison of experimental results with theory

In Fig. 2 typical experimental results are shown for the normalized read signal as a function of bit density at transducer spacings of 0.125 μm, 0.25 μm, and 0.450 μm, respectively. From the data we clearly observe the strong effect of transducer spacing on the roll-off behavior. In particular, we note that an increase in flying height from 0.125 μm to 0.45 μm corresponds to an almost 50 percent decrease in the −6 dB packing density, indicating the importance of close spacings for high density recording.

In Fig. 3 we have replotted the experimental data for 0.45 μm flying height together with the predictions of the simple theories. This graph shows that the assumption of perfect step function recording with $a = 0$ is in better

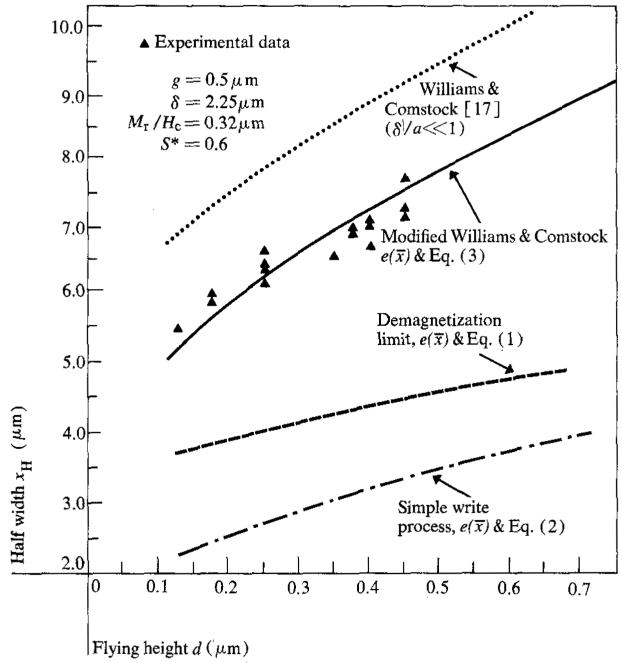

Figure 4 Variation of half-pulse width of isolated pulses as a function of flying height ($H_c = 2.39 \times 10^4$ A/m).

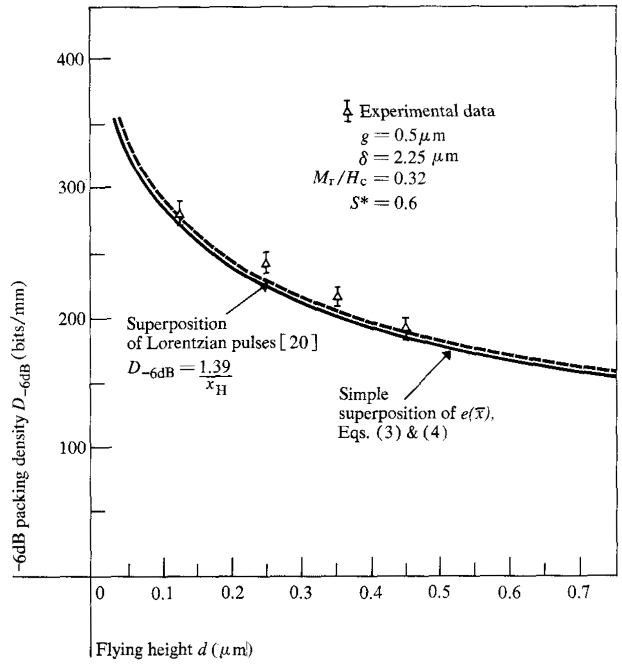

Figure 5 Comparison of theoretical prediction with experiment for packing density vs flying height for a given design point.

agreement with the experimental falloff characteristics than the predictions of the Wallace equation; however, it is apparent that neither of the two theoretical predictions comes at all close to the experimental results. Noticeable deviations are likewise observed for the theoretical calculations with a from either the simple write criterion [Eq. (2)] or demagnetization limit [Eq. (1)], although these latter predictions are improvements compared to both the Wallace equation and the perfect step function assumption. Excellent agreement, on the other hand, is observed with our experimental data if we use the modified write-process slope criterion [Eq. (3)] for calculating a. Possible reasons for this result will be discussed in a later section; here we emphasize only that the theoretical predictions were obtained by using the optically measured flying heights rather than fictitious effective spacings. For comparison, note that the Wallace equation requires an effective spacing of 2.25 μm to reach agreement with our experimental data. Although the results of the Wallace equation should be compared with digital recording results only at very high densities [11], it is common practice in digital tape recording to use the Wallace equation at intermediate densities, for which the above effective separation of several micrometers is typical [7].

Very similar theoretical-experimental agreement has also been obtained for another magnetic medium with $H_c = 4.06 \times 10^4$ A/m (510 Oe), and $d = 0.25$ μm.

Typical measurements for the half pulse-width of isolated pulses are shown in Fig. 4 as a function of flying height, together with theoretical predictions. Note that the original Williams-Comstock theory [17] for thin media overestimates the half-pulse width, while the simple theories with a from Eqs. (1) or (2) underestimate the experimental results. Again, x_H using $e(\bar{x})$ from [13] with a from Eq. (3) is found to agree best with our data.

In addition to the frequency response and half-pulse width of digital signals, a widely used figure of merit in designing recording systems is the −6 dB density, and it appears prudent to compare our experimental data with theoretical predictions for this important design point. This is shown in Fig. 5, where we plot the −6 dB density as a function of flying height for the 0.5 μm gap-width head. The results are mainly a restatement of our previous findings, i.e., that the resolution of the recorded signals depends strongly on flying height and that the modified write-slope criterion agrees well with the experiment.

Discussion

The results presented in the previous section show that substantial discrepancies exist between experimental results and theoretical predictions if the Wallace equation is used or if the transition parameter a is calculated from either the demagnetization limit or the simple write-slope criterion. In this respect, the present results agree well with those of our earlier investigation [1], in which we found increasing deviation between theory and experiment in the limit of very small transducer spacings. On the other hand, we notice from examination of Figs. 3-5 that theoretical predictions for frequency roll-off and half-pulse width are in excellent agreement with our experimental data if we calculate the transition parameter a using the Williams-Comstock modified theory.

Several points concerning the measurement accuracy of transducer spacing, medium thickness, and transducer gap width seem to be in order. First, we reiterate that the resolution of our interferometric spacing measurement is about $\pm 0.025\ \mu m$. Relative spacing errors should increase as the transducer spacing decreases. These errors may be still larger if magnetic tape is used instead of clear Mylar tape, because of the difference in surface roughness. Although spacing measurement seems to introduce the potentially largest uncertainty, an error of at least 10 percent must also be considered for the spatial variations in thickness of the recording medium and for measurement limitations. In addition, a substantial error is introduced by the gap width measurement, although it would appear at first that this value could be determined most accurately using electron microscopy. Examination of electron photomicrographs, however, shows that the gap of a magnetic head is not as uniform and parallel as assumed in the idealized model of Fig. 1, and a variation of about ± 10 percent may be expected for the overall average value of gap width.

Discrepancies between experimental results and theoretical predictions are further increased by uncertainties in measurement of magnetic tape properties as well as by a certain amount of arbitrariness introduced in selecting the proper value of the write current. In fact, the write current should ideally be optimized not only at each new flying height, but also at each new frequency. This continual optimization is very cumbersome, and since the maximum signal amplitude as a function of write current was found to be relatively flat, we chose the write current so as to nearly optimize the signal amplitude at bit densities up to approximately 250 bits/mm at each flying height. This clearly introduces an additional error in our experimental results.

We may thus conclude that any reasonable agreement between experiment and simple theories to within, say, 30 percent, would be remarkable and could not be expected a priori. Returning now to the excellent agreement between our experimental results and theory using the modified write-slope criterion, we recall first that the transition parameter a in Williams-Comstock theory is calculated by considering the effect of the write process as well as the effect of demagnetization. Thus the Williams-Comstock analysis goes beyond the scope of Eqs. (1) or (2), where either the write process or demagnetization is neglected.

On the other hand, we notice that a large number of approximations and simplifying assumptions were made in deriving $e(\bar{x})$, the most questionable assumptions being those of uniform magnetization in the x direction, negligible y magnetization and arc-tangent-like transitions between opposite magnetization regions. Because of all these assumptions, one can expect only gross phenomena to be predicted by the simple theories, and a detailed picture of the physical phenomena at the head-medium interface must be left to self-consistent numerical computations. Furthermore, it is well known that at high densities the field penetration is not large enough to saturate the magnetic layer completely if one optimizes the read signal for resolution. In this latter case, the thickness of the medium in the theoretical calculation must be reduced to a smaller value. This clearly leads to a certain degree of ambiguity, since one has to determine the "effective" depth of field penetration. In the present case, however, we optimized the write current so as to allow complete saturation of the recording medium.

We emphasize that our present experimental results are limited in that only a small range of magnetic tape parameters has been investigated. It is planned to extend the present investigation to include thinner particulate media as well as media with large M_r/H_c values. If these studies also agree with theoretical predictions, it would appear that the notion of "effective spacing" can be avoided.

The ultimate verification of the above conjecture, of course, will depend on a reliable experimental measurement of the transition parameter a, and it is hoped that some time in the near future reliable measurements of a will become available.

Acknowledgment

We acknowledge the capable help of G. Nelson in the experimental part of this investigation.

References

1. F. E. Talke and R. C. Tseng, *IEEE Trans. Magn.* **MAG-9,** 133 (1973).
2. D. F. Eldridge, *IRE Trans. Audio* **AU-8,** 42 (1960).
3. P. I. Bonyhard, A. V. Davies, and B. K. Middleton, *IEEE Trans. Magn.* **MAG-2,** 1 (1966).
4. B. K. Middleton, *IEEE Trans. Magn.* **MAG-2,** 225 (1966).
5. K. Teer, *Phillips Res. Reports* **16,** 469 (1961).
6. J. K. Alstad, *IEEE Trans. Magn.* **MAG-9,** 327 (1973).
7. J. K. Alstad, private communication.
8. J. Potgiesser and J. Koorneet, *IERE Conference Proceedings*, No. 26, 203, 1973.
9. G. Bate and L. P. Dunn, *Digests of Intermag. Conference*, Paper No. 14.6, 1974.
10. R. I. Potter and R. J. Schmulian, *IEEE Trans. Magn.* **MAG-7,** 873 (1971).
11. R. L. Comstock and M. L. Williams, *IEEE Trans. Magn.* **MAG-9,** 342 (1973).
12. C. Lin and R. Sullivan, *IBM J. Res. Develop.* **16,** 269 (1972).

13. D. E. Speliotis and J. R. Morrison, *IBM J. Res. Develop.* **10,** 233 (1966).
14. R. I. Potter, *J. Applied Phys.* **41,** 1647 (1970).
15. D. E. Speliotis, *J. Applied Phys.* **39,** 1310 (1968).
16. R. O. McCary, *IEEE Trans. Magn.* **MAG-7,** 4 (1971).
17. M. L. Williams and R. L. Comstock, *AIP Conference Proceedings on Magnetism and Magnetic Materials*, No. 5, Rept. 1, 738, 1971.
18. B. Kostyshyn, *IEEE Trans. Magn.* **MAG-2,** 236 (1960).
19. N. Curland and D. E. Speliotis, *IEEE Trans. Magn.* **MAG-7,** 538 (1971).
20. A. J. Kosters and D. E. Speliotis, *IEEE Trans. Magn.* **MAG-7,** 544 (1971).
21. J. C. Mallinson and C. W. Steele, *IEEE Trans. Magn.* **MAG-5,** 886 (1969).
22. R. L. Wallace, Jr., *Bell Syst. Tech. J.* **30,** 1145 (1951).

Received December 19, 1974

The authors are located at the IBM Research Laboratory, Monterey and Cottle Roads, San Jose, California 95193.