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A COMPUTER SIMULATION OF DIGITAL RECORDING

First Quarterly Progress Report
29 December 1966 through 31 March 1967

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A COMPUTER SIMULATION OF DIGITAL RECORDING

by

J.C. Mallinson

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1.0 INTRODUCTION

The experimental study of digital recording processes is greatly hindered by the difficulty in obtaining nonstandard tapes and heads of sufficiently high quality that the test results may be considered valid. These remarks are particularly true in the case of tapes where the difficulty in making single parameter changes is an additional complication.

On the other hand, the theoretical study of digital recording is greatly complicated by the number of significant variables, the spatial non-uniformity of the head-tape interactions and, above all, the non-linearity of the record process.

For these reasons a computer simulation of digital recording has been undertaken. This report will discuss the makeup of the computer programs and some of the results presently obtained.

2.0 THE COMPUTER PROGRAM

The program may be divided into a series of steps corresponding to those ocurring in the actual physical system. The steps are: recording, demagnetization, remagnetization, readout and differentiation. All of the steps except the first are treated as linear, super-imposable, harmonically analysable processes. Due to the tape magnetic hysteresis, the recording phase is non-linear and may not be treated harmonically.

Two programs have been completed to date which consider isolated transitions and periodic transitions. For both programs, the remanent tape magnetization is assumed to be entirely longitudinal*. The magnetization, M, written at a point on the tape, when the longitudinal component of the write head magnetic field, H_x, at that point has its largest magnitude, is given by a simple non-interacting particle model such that:

$$
\begin{aligned}
M &= 0 \quad \text{IF } |Hx| < H_1 \\
M &= \frac{1}{2}\left(Hx - \frac{Hx}{|Hx|}H_1\right) \qquad (1) \\
M &= \pm 1 \quad \text{IF } |Hx| > H_2
\end{aligned}
$$

* D.F. Eldridge, IRE Trans. Audio, AU-8, pp. 42-57, April 1960.

where χ is the susceptibility of the magnetic material, (see Fig. 1) and H_1 is the threshold value of magnetic field at which switching can take place. Thereafter, changes in magnetization, ΔM, resulting from a subsequent local extreme of H_x seen at that point, are given by

$$
\begin{aligned}
&\Delta M = 0 \text{ IF } |Hx| < H_1 \\
&\Delta M = \chi \left(Hx - \frac{Hx}{|Hx|} H_1 \right) \\
&\Delta M = \pm 2 \text{ IF } Hx > H_2
\end{aligned}
\qquad (2)
$$

Note that Eqs. (1) and (2) do not account for demagnetizing effects. These effects are computed by techniques indicated below.

The specific form of the record head field longitudinal component used is *

$$
Hx = \frac{H_o}{\pi} \left[\tan^{-1}\left(\frac{x + \frac{g}{2}}{Y} \right) + \tan^{-1}\left(\frac{x - \frac{g}{2}}{Y} \right) \right]
$$

where H_o is the deep gap field and g is the gap length.

For the first of these programs, the write head current executes a single transition from $-I_o$ to I_o as shown in Fig. 2. Initially, the magnetization is computed by Eqs. (1) and (2) for a number of values of x (the longitudinal distance along the tape) and of y (the distance from the write head to the given point, in the direction normal to the tape surface). For each value of x, an average value of magnetization with respect to y, over the tape thickness, $M_a(x)$, is then computed. Next, the flux generated in the read head is computed by an algorithm

* O. Karlquist, Trans. Royal Inst. Techn. Stockholm, 86, 1954

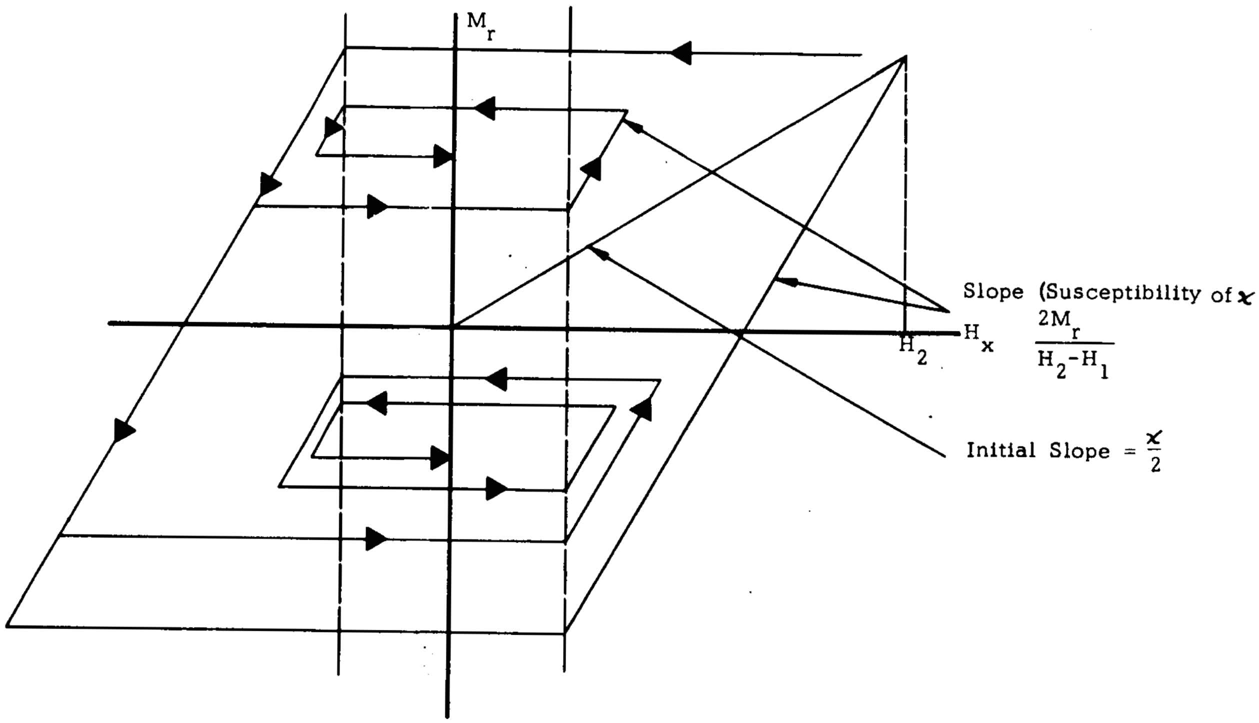


Fig. 1 Non-Interacting Model of Tape Remanence

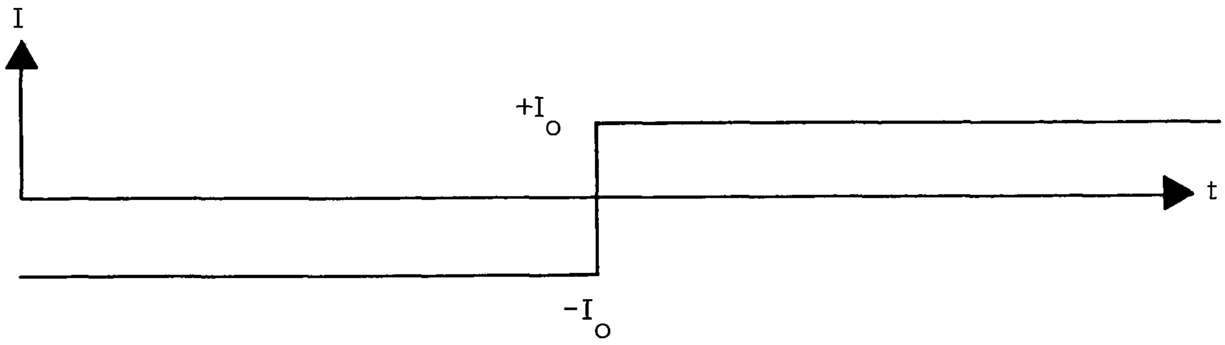


Fig. 2a Write Head Current for the First (Fourier Transform) Program

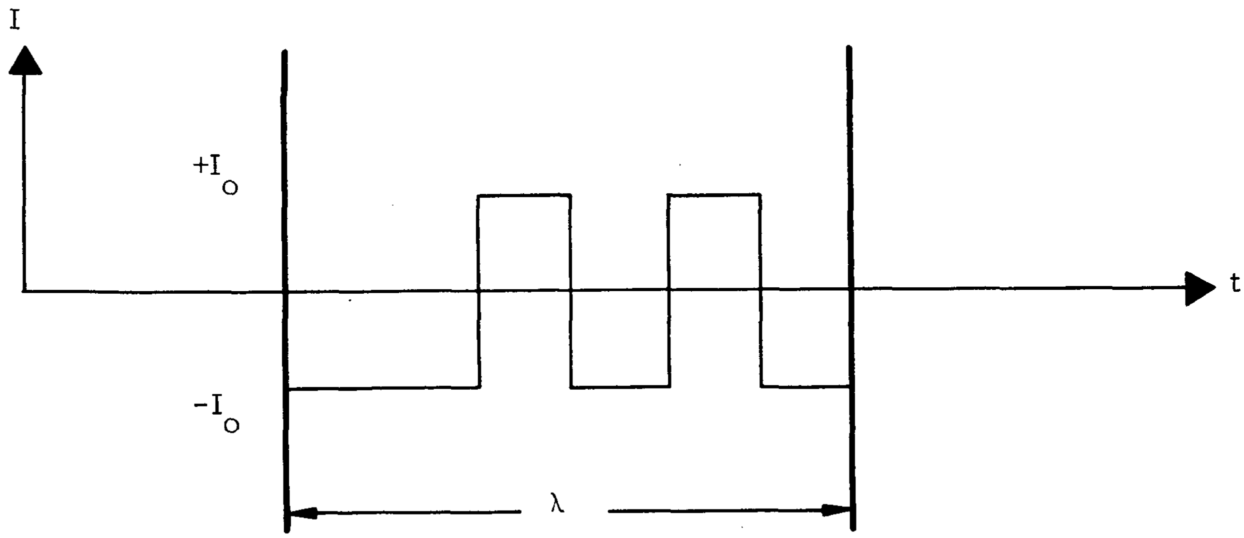


Fig. 2b Typical Six Bit Word Head Current for Second (Fourier Series) Program

that accounts for the effects of demagnetization and remagnetization in the following five steps.

(1) The Fourier transform N(k) of T(x), given by

$$T(x) = M_a(x) - \frac{2}{\pi} M_m S(k_u x) \tag{3}$$

for a large number of values of the wave number, k, is computed by numerical integration where

$$M_m = \lim_{x \to \infty} M_a(x) = -\lim_{x \to -\infty} M_a(x) \tag{4}$$

$$S(k_u x) = \int_0^x \frac{\sin(k_u t) dt}{t} \tag{5}$$

and k_u is the largest value of the wave number k for which N(k) is computed. The second term on the right side of Eq. (3) is needed because there is no Fourier transform of $M_a(x)$. This, in turn, results from the fact that, as one can see from Eq. (4) and from Fig. 2, the integral

$$\int_{-\infty}^{\infty} M_a(x) e^{-jkx} dx$$

does not converge.

On the other hand*

* E. Jahnke and F. Emde, "Tables of Functions", Fourth Edition Dover Publication, New York.

$$|S(k_u x)| = Si(k_u|x|)$$

and

$$\lim_{x\to\infty} S(k_u x) = \frac{\pi}{2}$$

so that with Eq. (3), (4) and (5)

$$\lim_{x\to\infty} T(x) = 0$$

with the result that a Fourier transform for T(x) exists. The function $S(k_u x)$ has the convenient property that its Fourier transform is 1/k for $k \leq k_u$ and is zero for $k > 0$.

(2) The Fourier transform P(k), of

$$U(x) = M_a(x) - \frac{2}{\pi} M_m S(k_l x) \tag{6}$$

is computed, where $k_l \ll k_u$. Then

$$P(k) = N(k) + \frac{2M_m}{\pi k} \tag{7}$$

The need for this step is explained below.

(3) To obtain the Fourier transform of the read head flux, we multiply P(k) by D(k), a factor that accounts for both demagnetization and the wavelength-dependent effects of the reading process, to yield

$$Q(k) = D(k)P(k)G(k) \qquad k_l \leqslant k \leqslant k_u \tag{8}$$

//

The factor D(k) has been provided by Mallinson*, and is given by

$$D(k)=\frac{\mu_2\sinh(kd)+\cosh(kd)-1+\dfrac{(\mu_1-\mu_2)(\mu_1\sinh(kd)+\cosh(kd)-1)(\sinh(kd)+\cosh(kd)+\mu_2)}{\mu_1\mu_2\left(2\cosh(kd)+\left(\mu_1+\frac{1}{\mu_1}\right)\sinh(kd)\right)}}{\mu_1 kd\left[\sinh(kd)\left(\mu_2\sinh(ka)+\frac{1}{\mu_2}\cosh(ka)\right)+\cosh(kd)\,e^{ka}\right]} \tag{9}$$

The factor G(k) is the usual gap loss term given by:

$$G(k)=\frac{\sin\frac{kg}{2}}{\frac{kg}{2}} \tag{10}$$

(4) The inverse Fourier transform, W(x') of Q(k) is computed for a large number of values of x', the longitudinal displacement of the tape during the read process.

(5) The read head flux is computed by

$$\Psi(x')=W(x')+\frac{2}{\pi}M_m S(k_1 x') \tag{11}$$

* J.C. Mallinson, "Demagnetization Theory for Longitudinal Recording", IEEE Transactions on Magnetics, Vd. MAG-2, No.3, September 1966.

Ideally, we would like to compute a Fourier transform for $M_a(x)$ over the entire spectrum of k from $k = 0$ to $k = \infty$. Since this cannot be done, we must take care to evaluate P(k) (in Eq.(7) and Eq.(8)) over a finite interval on k that is adequate to permit an accurate evaluation of $\Psi(x')$ (in Eq. (10)). In other words, the upper and lower limits of this interval of k, k_u and k_l must be carefully chosen. From Eq. (8) and Eq. (10) one can see that the k-spectrum of $\Psi(x')$ is affected by D(k) only for values of k equal to or greater than k_l. If k_l is chosen too high, the full effect of demagnetization is not reflected in the computed $\Psi(x')$. Alternatively, the value of k_u must be high enough that N(k) evaluated for $k_l \leq k \leq k_u$ accurately represents the Fourier transform of T(x).

Finally, the first derivative of $\Psi(x')$ with respect to x', which is proportional to the output voltage as a function of time, is computed by numerical differentiation.

For the other program, the write head current executes a signal that is periodic in time. During each period, there is a sequence of six digital pulses as shown in Fig. 2. The program has the facility for using any desired sequence. Since the magnetization that is recorded on tape is periodic in x, the distance longitudinally along the tape, it has a Fourier series representiation. The program computes the coefficients for any desired number of harmonics by numerical integration. These coefficients are then multiplied by D(nk) and G(mk) (from Eq. (8)) where m is the number of the harmonic and

$$K = \frac{2\pi}{\lambda}$$

where λ is the wavelength of the six-bit period. The new coefficients are those of the Fourier series representiation of the $\Psi(x')$, the head flux as a function of x', the longitudinal displacement of the tape with respect to the read head. From these coefficients, $\Psi(x')$ and

$$\frac{d\Psi(x')}{dx'}$$

are computed.

3.0 DISCUSSION OF THE SINGLE PULSE PROGRAM RESULTS

3.1 Introduction

In the computer simulation of an IBM compatible isolated pulse it is necessary to specify four geometrical and four magnetic parameters. They are:

	Standard Value
Head-to-tape spacing (a)	20 μins.
Coating thickness (d)	400 μins.
Record gap length (g record)	500 μins.
Reproduce gap length (g reproduce)	250 μins.
Deep gap record field (H_o)	1500 oe
Range of switching fields (H_1/H_2)	200 - 400 oe
Demagnetization permeability μ_1	4
Remagnetization permeability μ_2	2

One of these parameters, the head-to-tape spacing, is not known with any precision. Others are only linearized approximations. It was felt to be worthwhile to compute the output pulse as each of these parameters was varied in turn, the remainder being held constant. In addition to giving very considerable confidence that the program is functioning correctly and that no one parameter is of predominant importance, this procedure also gives a clear insight into the whole recording-demagnetizing-remagnetizing-reproducing cycle.

3.2 Theoretical Background

Before discussing the computer results, it will prove to be helpful to consider the results of three idealized calculations. The first considers the playback pulse expected from an idealized zero length transition of magnetization. According to Eldridge* and many subsequent authors, the output pulse is

$$\mathcal{E}(x) \propto \log \frac{(a+d)^2 + x^2}{a^2 + x^2} \tag{12}$$

If we substitute a = 20 μins, d = 400 μins, we find the 20% to 20% pulse width would be approximately equal to 450 μins. This pulse width is much smaller than the value 1600 μins observed experimentally and the difference can only be attributed to the finite length of the magnetization transitions. This length may be due to either the original record head field gradient effect or the subsequent demagnetization process. If it is assumed that the magnetization transition has the (convenient) form

$$M = \frac{2M}{\pi} \tan^{-1}\left(\frac{x}{\ell}\right) \tag{13}$$

and is uniform at all depths in the tape, and that no remagnetization occurs (i.e. $\mu_2 = 1$) it may be shown** that the output pulse is

* D.F. Eldridge, IRE Trans. Audio Au9, 49 (1960)
** J.J. Miyata and R.R.Hartel, IRE Trans. Elect.Comp. EC-8, 159 (1959).

$$\varepsilon(X) \propto \log \frac{(a+d+\ell)^2+x^2}{(a+\ell)^2+x^2} \tag{14}$$

This expression may be made to fit the observed pulse by using $\ell \simeq$ 300 μins. This corresponds to a magnetization transition shown in Fig. 3.

Let us now consider the linearized transition also shown (dashed line) in Fig. 3. It is drawn such that the slope at the origin coincides with that shown by the arctangent function. This linearized transition extends over a longitudinal distance ($2x_o$) equal to $2\frac{\pi}{2}$ • 300 $\simeq$ 950 μins. We may compare this figure with that arrived at by simple estimates of the effects of demagnetization. By the somewhat ad hoc process of setting the maximum internal field equal to the coercive force of the tape coating, Speliotis and Morrison* give the equation

$$\ell = 2x_o = d \cot\left(\frac{\pi}{2} \quad \frac{H_c}{4\pi M_r}\right) \tag{15}$$

For standard γFe_2O_3 tape H_c = 300 oe, $4\pi M_r$ - 1250 gauss, yielding a transition length of approximately 900 μins, which is an excellent agreement.

We see, therefore, that at least in the case of saturation recording on 400 μins thick γ Fe_2O_3, the final transition length of the magnetization is likely to be governed by demagnetization effects,

* D.E. Speliotis and J.R. Morrison, IBM Journal 233, May 1966

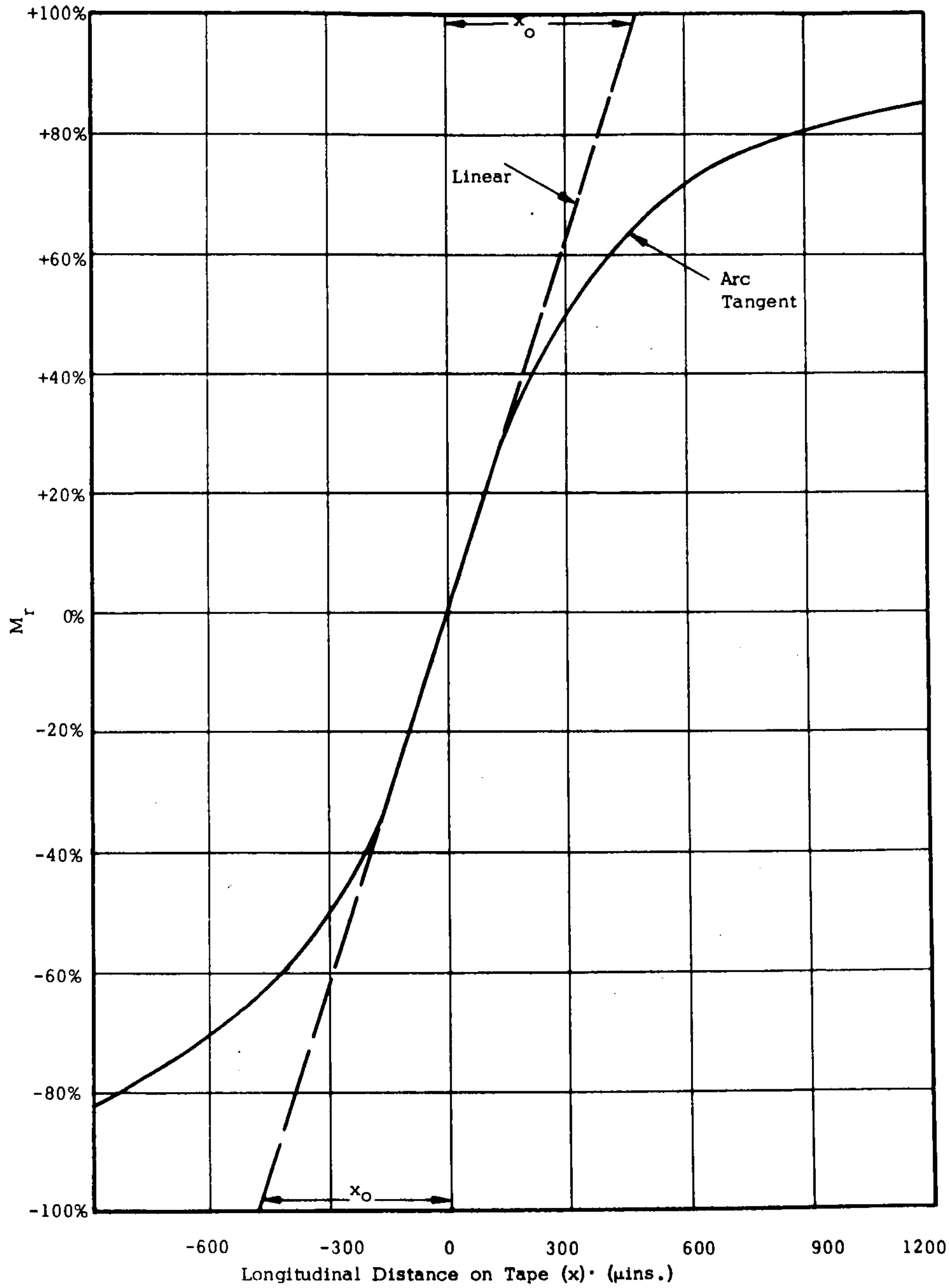


Fig. 3 A Magnetization Transition of the Form: $M = \frac{2M}{\pi} \tan^{-1} \frac{x}{\ell}$ (where $\ell = 300$ µins.) which would give a 20% - 20% isolated pulse width of 1600 µins.

to be about 900 μins long, and to give rise to a 20% - 20% output pulse width of about 1600 μins. It is, of course, difficult to separate effects, but broadly speaking, about 1000 μins of the pulse width observed is due to demagnetization and about 500 μins due to the read process. Both effects can, of course, be reduced by either using thinner tape or non-saturating record currents.

3.3 Computer Results

3.3.1 Variations of the head-to-tape spacing (a)

Table 1 Effect of Variations of the Head-to-Tape Spacing (a)

a (μins)	ϵ_{peak}	Δx (μins)	20% - 20% width (μins)
100	14	400	1800
60	16.5	400	1550
40	18	400	1450
20	19	400	1300
10	21	400	1150
5	22	400	1100

Note: Δx is the position of the reproduce pulse peak relative to the record gap center line (i.e. it is 400 μins. downstream in this case).

ϵ_{peak} is in relative units only.

Comments:

It is of interest, practically, that it scarcely matters whether we set the highly speculative head-to-tape spacing equal to 10 or 20 μins or even 40 μins. The variations in ϵ_p and 20% width thus incurred are only 15% and 25% respectively.

Theoretically the explanation is quite simple. The transition length, ℓ, is large compared to the head-to-tape spacing, and thus

$$\mathcal{E}(x) \propto \log \frac{(a+d+\ell)^2 + x^2}{(a+\ell)^2 + x^2} \longrightarrow \log \frac{(d+\ell)^2 + x^2}{\ell^2 + x^2}$$

3.3.2 Variations in coating thickness (d)

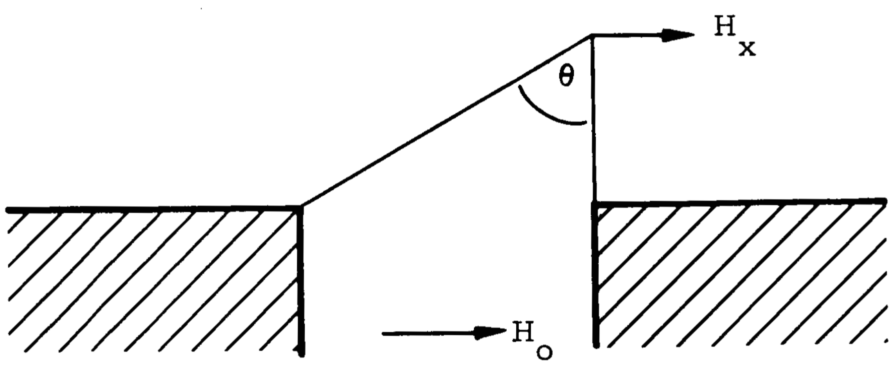
Because of the certainty of this (micrometer) measurement, this test was not made.

3.3.3 Variations in the record gap length (g record)

This test was conducted with six different gap lengths and in each case the record current (deep gap field) was adjusted to give one half, once and twice the saturation level. This was determined as follows. The Karlquist arctangent head field expression may be shown to be

$$H_x = H_o \left(\frac{\theta}{\pi}\right)$$

where θ is the angle (radians) subtended by the gap.



The maximum value of H_x occurs on the gap center line. Saturation level is defined here as being that deep gap field which just yields a field of 400 oe at the deepest tape layers, i.e.,

$$(H_0)_{sat} = \frac{400\pi}{2\tan^{-1}\frac{g}{2(a+d)}}$$

Table 2 Effect of Variations in the Record Gap Length (g Record)

H_o (oe)		ϵ_p	Δx	20%
2250	g record = 100 µins	15.5	200	1100
4500		19	250	1200
9000		18.5	400	1350
575	g = 500 µins	14	250	1100
1150		20	350	1200
2300		18.5	550	1350
350	g = 1000 µins	6.2	400	1300
700		19.5	600	1300
1400		19	700	1300
300	g = 1500 µins	3.8	600	1500
600		19	750	1250
1200		18.5	900	1350
-	g = 3000 µins	-	-	-
480		16.5	1400	1550
960		18	1700	1300
222	g = 5000 µins	0.5	2100	2800
445		15.5	2400	1750
890		18	2700	1400

Comments:

The principal observation is that, as is found experimentally* the pulse height and width at saturation are virtually independent of record gap length. This may be due to either the record field geometry or the subsequent effect of demagnetization. In Fig. 4 the record zone is drawn, to scale, for the cases of g = 100, 1000 and 3000 μins. The nesting circles are respectively the contours of constant longitudinal field strength equal to 400 and 200 oe. The shaded zone is the region of magnetization transition before any demagnetization occurs. It is quite clear that even if no demagnetization ever occurred, the output pulses derived from the g = 100 and g = 1000 μins record gaps would be virtually identical. Without demagnetization the g = 3000 μins pulse would, however, be over twice as wide. In fact, demagnetization does occur and we have already seen that it is likely to spread the transition out to almost 1000 μins. Consequently, all the pulses (g = 100, 1000 and 3000 μins) become nearly identical as the computer calculates.

3.3.4 Variations in the reproduce gap length

Table 3 Effect of Variations in the Record Gap Length

$g_{reproduce}$	ϵ_{peak}	Δx	20% width
0	21	-	1200
250	20	400	1250
500	16.5	400	1500
750	14	400	1700
1000	11.5	400	2050

* J.J. Miyata and R.R. Hartel, Ibid, Fig. 14

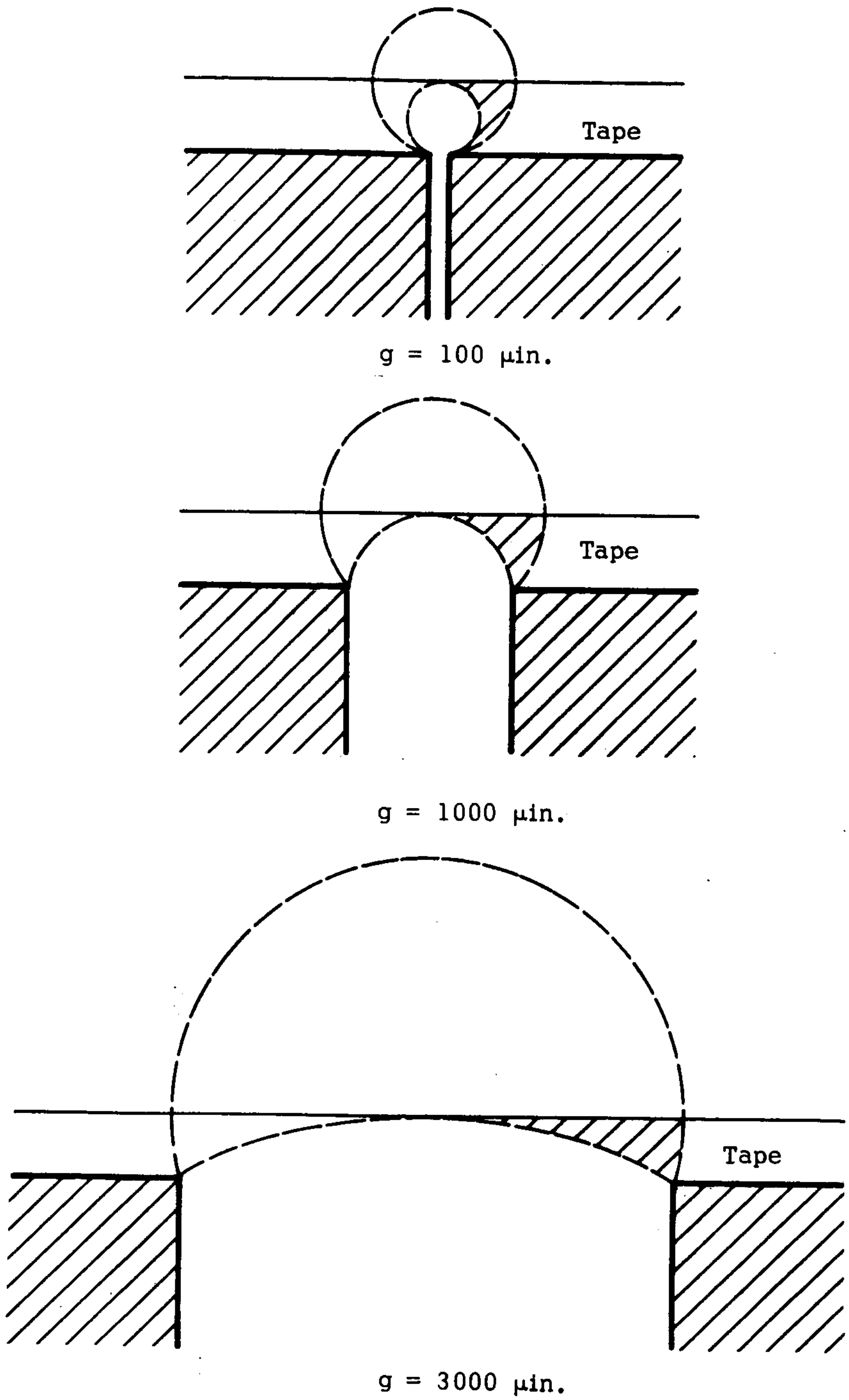


Fig. 4 Showing Record Zones at Saturation Level

Note that the computer is not calculating the well-known reproduce head flux shunting effects, caused by the non-infinite permeability of the head. Here we are concerned principally with the pulse sharpness, i.e. its harmonic content.

Comments:

The interesting observation here is that the case of a zero gap reproduce head, which will handle, without attenuation, even the highest harmonics, is very little better than the 250 μins head. This may be either a consequence of the finite record zone length or demagnetization, either of which places an effective upper limit on the divergence of the magnetization, (approximately $\frac{dMx}{dx}$ in this case) and thus an upper limit on the pulse harmonics.

It would thus seem that, in practice, nothing will be gained by using reproduce gaps of length less than the coating thickness. The writer knows of no experimental data concerning this.

3.3.5 Variations in the deep gap record field (H_o)

Table 4 Effect of Variations in the Deep Gap Record Field

H_o (oe)	ϵ_p	Δx	20% width
3000	17	600	1400
2500	18	550	1350
2000	19	500	1300
1500	19	400	1300
1000 (saturation)	19.5	300	1200
500	14.5	200	950

Comments:

The results above are precisely as found experimentally*.

The record zone geometries appropriate to one, two and three times saturation are drawn to scale in Fig. 5. Here we may note that, in the absence of demagnetization, the principal shortcoming of the record head field is not the much discussed "gradient" effect but rather the phase shift or longitudinal displacement of the transition zone of the various depths in the tape. Again, however, we must recall that the effects of demagnetization will effectively obliterate all the detail on a scale smaller than about 1000 μins. Consequently all the pulses above the saturation level become virtually identical.

3.3.6 Variations of the tape switching fields (H_1/H_2)

Table 5 Effect of Variations of the Tape Switching Fields

H_1/H_2(oe)	ϵ_p	Δx	20% Width
200/400	19	400	1300
100/500	18	400	1400
50/550	16.5	400	1500

Note: In order that the computer program may be kept simple, all of these pairs of switching fields are made to be symmetrical about the tape coercive force, 300 oe.

* For example, see J.J. Miyata and R.R. Hartel, Ibid, Fig. 10

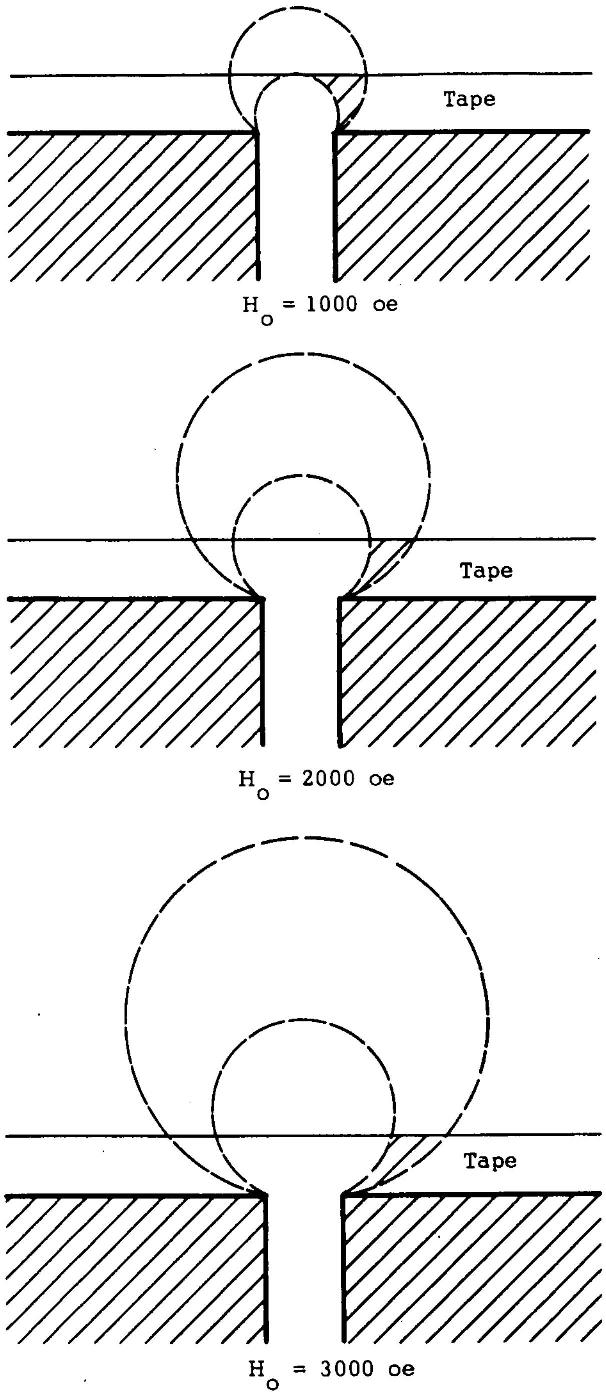


Fig. 5 Showing Record Zones at Various Values (1x, 2x, 3x, Sat.)

Comments:

Figure 6 shows the transition zone geometry before demagnetization. Since the zone length is not large compared with the demagnetization relaxation length, very little detail survives. This case is very similar to that just considered (i.e. variation of deep gap field) and no further comment is required.

3.3.7 Variations in the tape permeabilities (μ_1 and μ_2)

Table 6 Effect of Variations in the Tape Permeabilities

H_1/H_2(oe)		ϵ_p (g = 0)	20% Width	ϵ_p (g = 250)	20% Width
$\mu_1 = 1$	$\mu_2 = 1$	32	800	28	900
$\mu_1 = 2$	$\mu_2 = 1$	24.5	900	21	1100
3		20	1100	17.5	1400
4		17	1300	15	1500
5		15	1500	13.3	1800
$\mu_1 = 2$	$\mu_2 = 2$	31	900	27	1000
3		25	1000	22.5	1200
4		21	1100	19	1300
5		18.5	1300	16.5	1400

Note: This calculation was repeated, as shown above, for the case of an ideal (g = 0) reproduce head since it is of interest to be able to separate tape and head effects.

Comments:

First we note that the case of completely reversible demagnetization ($\mu_1 = 2$, $\mu_2 = 2$) yields virtually the same result as the case

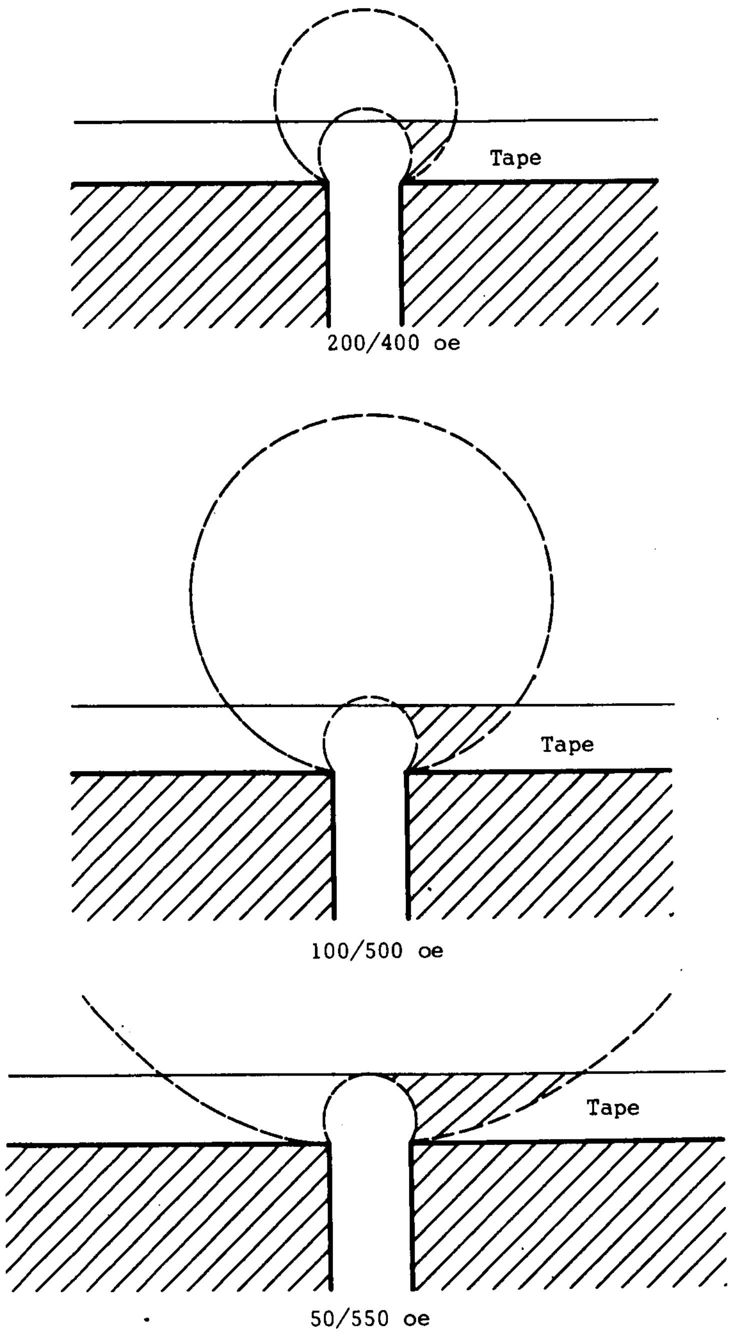


Fig. 6 Showing Record Zones For Various Switching Fields

of no demagnetization ($\mu_1 = 1$, $\mu_2 = 1$). This is, of course, to be expected. We may note, in passing, that the reversible case is that treated by Westmijze* and that previous computer simulations using Westmijze's equation** are in effect presuming the demagnetization does not affect the output pulse in any way.

Next we notice that there is very little difference between the g = 0 and g = 250 μins reproduce gap data. It has already been pointed out that this could be due either to record zone or demagnetization effects. It is interesting that the effect persists even for no demagnetization ($\mu_1 = 1$, $\mu_2 = 1$), and we may explain this by noting that the average record zone length is generally about 300 μins. We conclude then that even the original transition is low in harmonics of wavelength less than 300 μins.

Finally, we notice that as anticipated, the effect of increasing μ_1 is to spread the pulse out and conversely with μ_2. It may be shown that, at the short wavelength limit ($kd = \frac{2\pi a}{\lambda} > 1$), the output signal becomes attenuated by a factor equal to $\mu_2 + 1/\mu + 1$ if the head-to-tape spacing is negligible ($ka = \frac{2\pi a}{\lambda} < 1$).

This condition is obeyed by wavelengths equal to the coating thickness ($kd \approx 6$, $ka \approx 0.3$). The attenuation factor is, for the standard case, $\mu_1 = 4$, $\mu_2 = 2$, equal to 0.6 and we may note with satisfaction that the computer yields peak voltage ratios of $\frac{21}{32} = 0.66$ and $\frac{19}{28} = 0.68$. To a good approximation then, the demag-remag cycle reduces the peak output by the factor $\mu_2 + 1/\mu_1 + 1$.

* W.K. Westmijze, Philips Res. Repts. 8, 1953

** For example, B. Kostyshyn, IRE Trans. Mag. 2 3, Sept. 1966

*** J.C. Mallinson, IRE Trans. Mag. 2, 3, 233, Sept. 1966

4.0 COMPARISON OF COMPUTER AND EXPERIMENTAL RESULTS

Throughout the preceding section the range of switching fields (H_1, H_2) was assumed to be 200 to 400 oe. Similarly the demagnetizing permeability was taken to be 4.

Recent measurements of the properties of standard γ Fe_2O_3 digital tape indicate that the range of switching fields is, at the 5% and 95% of maximum remanence points, 150 to 480 oe. In the interests of computational simplicity (specifically that the loop be described by a single value of susceptibility) the new standard values 100 and 500 oe have been adopted.

Similarly, it was realized that since the maximum remanence of standard tape is closer to 1250 gauss than to 1000 gauss, which value had been previously assumed, the (linearized) demagnetizing permeability is in fact equal to $\frac{1250}{300} + 1 \triangleq 5$.

The table of new standard parameters thus reads:

Head to tape spacing = 20 μins

Tape coating thickness = 400 μins

Record gap length = 500 μins

Reproduce gap length = 250 μins

Saturating deep gap field - 1500 oe

Switching fields of tape = 100 to 500 oe

Demagnetizing permeability = 5

Remagnetizing permeability = 2

These parameters lead to a pulse, shown in Fig. 7, which has a 20% - 20% width of 1600 μins. An experimental pulse is also shown in Fig. 7, and it will be seen that its 20% - 20% width is 1700 μins.

The detailed similarity of these two waveforms is considered to be excellent, particularly in view of the fact that all the computer calculation parameters listed above are, to the best of our knowledge, correct.

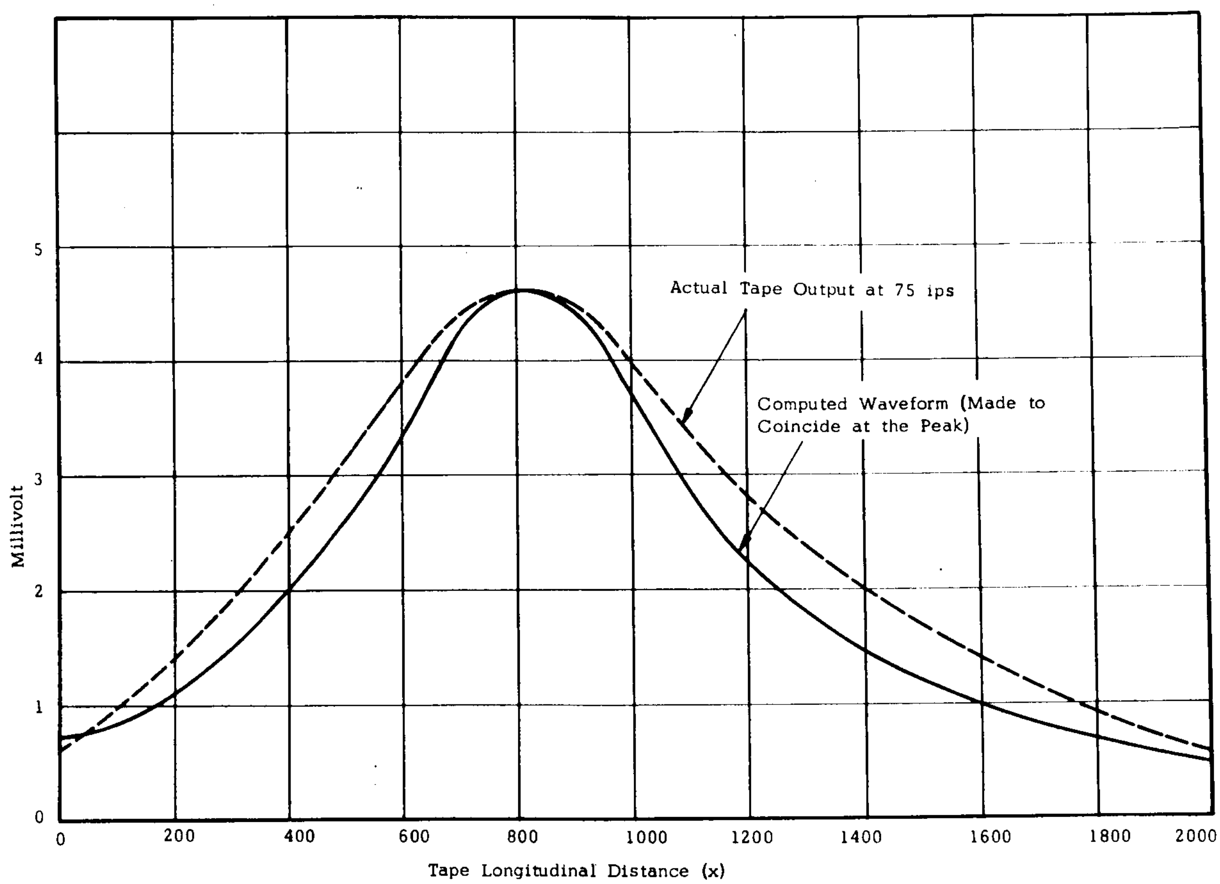


Fig. 7 Comparison of Compared and Experimental Single Transition Waveforms.

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5.0 CONCLUSIONS

At this stage of the contract, two computer programs have been written. Both produce output waveforms for isolated transitions which are within 20% of the experimental waveforms. This has been achieved, for the first time, without the imposition of unrealistic assumptions, such as very large head to tape spacing. The accuracy of the programs is due largely to the correct treatment of the demagnetization-remagnetization cycle.

It is now possible to proceed to investigate bit interaction effects with great confidence that all the major effects will be simulated correctly by the computer.