Propagation of Sense Signals in Large-Scale Magnetic Thin Film Memories

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Abstract—**A dynamic analysis has been made of the behavior of sense signals in large-scale magnetic thin film memories. The timed effects of attenuation, distortion, cross coupling and interconnection are superimposed on the transmitted waveforms. The computed signals can be used as a design guide to determine the length of sense lines, the number of intersecting word lines, the sense amplifier requirements, etc. The key limiting factors are the resistance of lines and the capacitance at the line intersections. Design criteria are discussed.**

I. Introduction

THE SENSE signal of magnetic thin film memory sustains various losses in the course of travel along the sense lines. These losses are: attenuation of magnitude, distortion in phase, reflections caused by interconnection of sense lines; and deterioration of waveform due to the cross coupling of word lines. By studying the propagation function of the sense lines, the attenuation and distortion can be calculated within the operating ranges of memory. The multiple reflections and deterioration can be expressed as a temporal sequence of traveling waves. Adding all the above effects together we may, as a guide to design, predict the waveform of sense signals at any point along the line.

By using traveling waves, the analysis yields a general solution suitable for both low and high speed applications. A straight strip-line in TEM mode is adopted for illustrative purposes, and the sense signal under consideration is measured from the sense wire to the ground plane.

II. Statement of the Problem

During the "Read" time, the magnetization of the film site is switched by the field of the driving current and an output signal is induced on the sense line. The potential of this signal is in series with the line. It propagates in both directions. One may postulate that its positive half travels in one direction and the negative half goes in another, as shown in Fig. 1.

Let us start with an ideal case in which the line has no discontinuities and no crossing of other lines. The two halves of the sense signal arrive at the preamplifier with a time separation depending on the location of the film site. Ignoring the reflections higher than the second order, we express in the Laplace transform (for the sake of convenience) the waveform of sense signal seen by the preamplifier as follows [1]

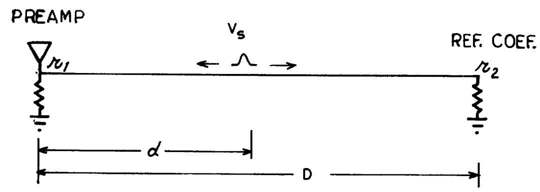

Fig. 1. An ideal sense line.

$$V(P) = \frac{V_s(P)}{2}(1 + r_1)\left[e^{-\gamma d} - r_2 e^{-\gamma(2D-d)}\right] \tag{1}$$

where r_1 and r_2 are the reflection coefficients at the two ends, γ is the propagation function, and V_s is the output signal of magnetic film.

The conventional design matches the line at the sensing end and shorts it to the ground at the other end. The above equation can be simplified as

$$V(P) = \frac{V_s(P)}{2} e^{-\gamma d}\left[1 + e^{-\gamma 2(D-d)}\right]. \tag{2}$$

The time separation of the two components within the brackets means the flattening of the composite waveform. The separation is maximum for the signal coming from the site nearest to the preamplifier, and minimum for the one from the farthermost site.

For simplicity, the output of the magnetic film will be approximated by a triangular wave as shown in Fig. 2. It is represented by the following source function

$$V_s(P) = V_s\left[\frac{1}{P^2}\left(\frac{1}{t_1} - \frac{e^{-Pt_1}}{t_1} - \frac{e^{-Pt_1}}{t_2} + \frac{e^{-P(t_1+t_2)}}{t_2}\right)\right]. \tag{3}$$

For an ideal line, the propagation function γ is $P\sqrt{LC}$ which means a time delay. By substituting (3) for $V_s(P)$ in (2), we then have the whole picture of a sense signal seen by the preamplifier, as shown in Fig. 3. However, the sense signal under study is in the submillivolts range. We have to take into consideration all degradations of the signal due to deviations from the ideal line characteristics, and we shall do so in the succeeding sections.

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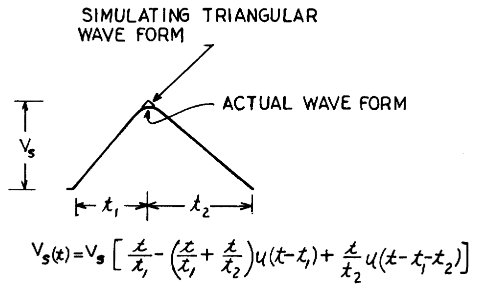

Fig. 2. Triangular wave representation of output signal.

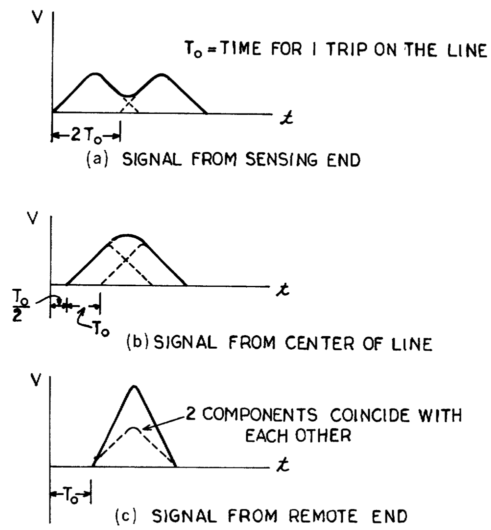

Fig. 3. Composite sense signals on an ideal line with exaggerated time separations.

III. Propagation Function

The quality of a transmission line depends entirely on the propagation function γ which is defined as follows:

$$\gamma = \sqrt{(R + PL)(G + PC)}, \qquad (4)$$

R, L, G, C being, respectively, the resistance, inductance, leakage, and capacitance per unit length of the line. The leakage G represents the conductance of dielectric loss in the memory array. It can be expressed as follows [2], [6]

$$G = \omega C \times \text{Power Factor}.$$

It is very small and can be ignored.

For magnetic film memories, the resistance of lines should be small to keep the attenuation of signals low. The sense signal has a short rise time which corresponds to high frequency components. We can assume

$$R < PL.$$

So it is permissible to expand (4) in the following fashion

$$\gamma = \sqrt{(R + PL)PC} \approx \left[P\sqrt{LC} + \frac{R}{2}\sqrt{\frac{C}{L}}\right]. \qquad (5)$$

The loading effect of the magnetic film is nil, because the sense signal does not perform any switching. The calculation of parameters L and C has been reported extensively in literature [3]–[5]. R will be discussed in Section III-A.

A. Resistance at High Frequency

Due to the skin effect, resistance increases as the operating frequency goes up. For a conductor with a thickness much greater than the depth of penetration, δ the skin-effect resistance, is [6]

$$\frac{1}{\sigma\delta} \text{ per square } \left(\delta = \sqrt{\frac{2}{\omega\mu\sigma}}\right)$$

where σ, of course, is the conductivity. For magnetic thin film memory applications, the line is extremely thin. Usually, the thickness of the conductor is comparable to, or less than the penetration depth. Therefore the above formula should be modified [6], [13].

$$\frac{1}{\sigma\delta}\left[\frac{\text{Sinh}\,\frac{2b}{\delta} + \text{Sin}\,\frac{2b}{\delta}}{\text{Cosh}\,\frac{2b}{\delta} - \text{Cos}\,\frac{2b}{\delta}}\right] \text{ per square.}$$

We have, then, the resistance term for a line W units wide and b units thick:

$$= R_{dc}[1 + \eta]/\text{unit length (see Appendix I)}. \qquad (6)$$

The η is plotted in terms of b/δ in Fig. 4.

Next, we come to an actual system, such as one shown in Fig. 5. The conductors in the middle layer are the sense lines. The current goes down the center conductor, and on the return trip it divides equally between two ground planes. With small off-center conductor displacements, the electric field pattern is confined as shown with dotted lines. For the case $2W > h$, the effective width W_1 is reported by McQuillan [7] as

$$W_1 = W + \frac{1}{\pi} 2h \log_e{}^2.$$

The condition $2W > h$ is easily met in magnetic film memories. In fact, it is mandatory in order to make a large-scale memory possible.

We extract one segment of the sense line matrix and redraw it in Fig. 6. Based on the discussion in the preceding paragraph, we should treat this segment as a union of two lines in parallel, each carrying one-half of the current. The total high-frequency resistance of the sense line can be arrived at in the following way

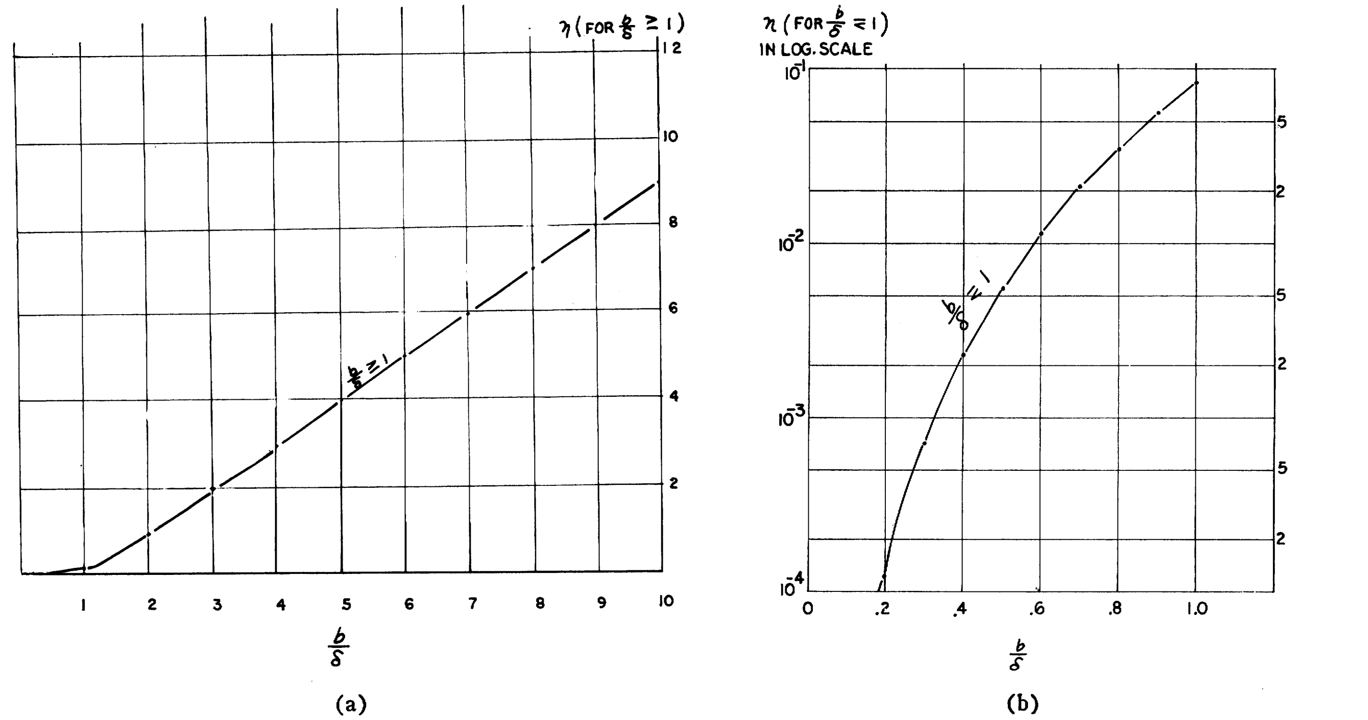

Fig. 4. η vs. b/δ.

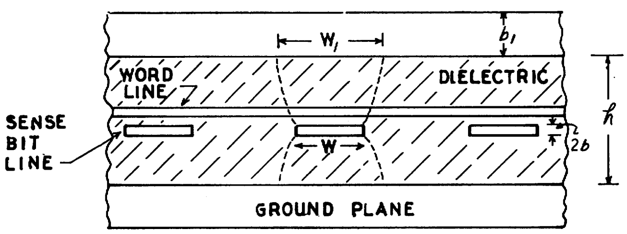

Fig. 5. A typical memory line matrix.

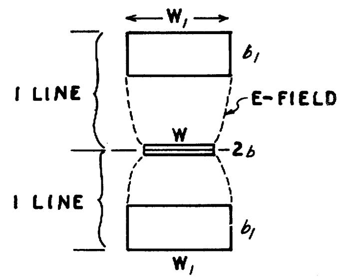

Fig. 6. Equivalent transmission lines for a sense line.

$$R = \frac{1}{2}\left\{\begin{array}{l}\text{Resistance of conductor of } \tfrac{1}{2} \text{ thickness} \\ + \text{Resistance of one ground plane of } W_1 \text{ width}\end{array}\right\}$$

$$= \frac{1}{2}\left\{R_{dc1}[1+\eta_1] + R_{dc2}[1+\eta_2]\right\} \quad [\text{see (6)}]$$

$$= \frac{R_{dc1}+R_{dc2}}{2} + \frac{1}{2}\left[R_{dc1}\eta_1 + R_{dc2}\eta_2\right]$$

$$= R_{dc} + H. \tag{7}$$

B. Attenuation and Distortion

With all the parameters known, let us go back to study the propagation function, which can now be expressed as

$$\gamma = P\sqrt{LC} + \frac{1}{2}\sqrt{\frac{C}{L}}R_{dc} + \frac{1}{2}\sqrt{\frac{C}{L}}H(P)$$

$$= \frac{P}{u} + \alpha + \Delta\beta. \tag{8}$$

u is the speed of travel, so the first term on the right side of the equation represents the delay or phase shift. The second term is commonly known as the attenuation function and the last one is the distortion [8].

The distortion function is complex and frequency-dependent. The whole expression is

$$\Delta\beta = \frac{1}{4}\sqrt{\frac{C}{L}}\left[R_{dc1}\eta_1 + R_{dc2}\eta_2\right]. \tag{9}$$

It is difficult to achieve an analytic solution. However, with a graph shown in Fig. 4, one can evaluate it at a known frequency, and treat it as a constant at that frequency. Therefore, we can rewrite (2) as follows

$$V(P) = \frac{V_s(P)}{2} e^{-(Pd/u)} e^{-\alpha d} e^{-\Delta\beta d} \cdot \left[1 + e^{-(P/u)2(D-d)} e^{-\alpha 2(D-d)} e^{-\Delta\beta 2(D-d)}\right]. \tag{10}$$

By substituting (3) for $V_s(P)$, it is readily solvable.

IV. Cross-Coupling Effects

When a sense line crosses over a word line, there is capacitance created at the intersection. This capacitor is basically a drain for the energy contained in the sense signal. It deteriorates the waveform while delaying the pulse at the same time. In a large scale memory, the sense line crosses numerous word lines. The capacitive couplings will be proved to have a very damaging effect on the signal.

The capacitors are shown shunting the sense line schematically in Fig. 7. The shunting branch has an impedance of $(1/PC)+(Z_w/2)$. The impedance of the word line Z_w is quite low (generally <25 ohms). On the other hand, the $1/PC$ term is in the order of 10–100 kilohms. (Assume a 20 nanoseconds rise time for the signal.) It is, therefore, allowable to drop the second term in this case.

The number of the capacitor branches runs into thousands in a large matrix. Usually, they are approximated as evenly distributed capacitance. This method is adequate for low speed applications. However, at high speed, the spacing between two capacitive branches is long electrically in respect to the rise time of the signals, even though it is short physically. A more accurate way should be used to describe the reflections. Therefore, it is proposed that the capacitors actually be treated as recurrent impedance discontinuities to the line. We can then accurately calculate the distortion and delay time as well. Observe the reflection lattice diagram at the bottom half of Fig. 7. The transmitted wave after one discontinuity is

$$T = \frac{\dfrac{2}{PC_c + 1/Z_0}}{\dfrac{1}{PC_c + 1/Z_0} + Z_0} = \frac{\dfrac{2}{Z_0C_c}}{P + \dfrac{2}{Z_0C_c}} = \frac{a}{P+a}$$

and the voltage at Point b due to discontinuities only is

$$V_b(P) = V_a(P)T^3 = V_a(P)\left(\frac{a}{P+a}\right)^3.$$

The reflections of the second order and above are negligible. If there are n crossings of word lines, we have then the transmission coefficient

$$T^n = \left(\frac{a}{P+a}\right)^n. \tag{11}$$

This factor should be included in (10) to find the waveform. Its effect can be demonstrated by translating into the time domain the product of (11) and the first component of the source function (3). We then have

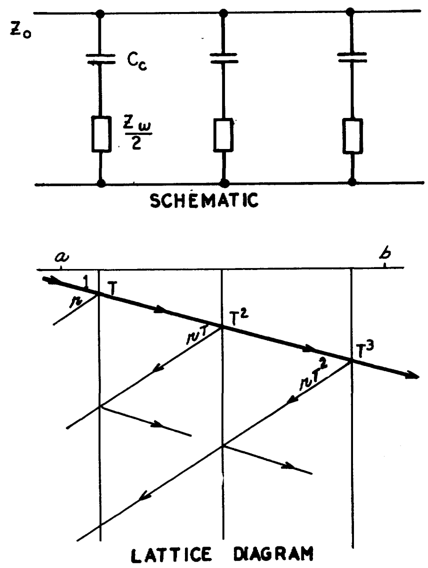

Fig. 7. Equivalent representation of capacitive couplings shunting a sense line.

$$\mathcal{L}^{-1}\frac{V_s}{t_1}\frac{1}{P^2}\left(\frac{a}{P+a}\right)^n = \frac{V_s}{t_1}a^n\int_0^t \frac{\tau^{n-1}}{(n-1)!}e^{-\tau}(t-\tau)\,d\tau$$
$$= \frac{V_s}{t_1}\left(t-\frac{1}{a}\right)\frac{\Gamma(n, at)}{\Gamma(n, \infty)} \tag{12}$$

(See Appendix II)

where $\Gamma(n, at)$ is the incomplete Gamma function. The result indicates that the original ramp function has to be degraded by the ratio of the incomplete Gamma function and the factorial function. For large "n," we can apply the Stirling's formula, and it can be shown that this ratio means a time delay of n/a and a slope of $\sqrt{2\pi n}/a$ [9], [10]. The net results are the flattening of the signal and, therefore, the reduction of the signal-to-noise ratio.

The composite sense signal should be rewritten by including the effects of cross couplings in the following. Let

$$F_1 = \frac{e^{-\alpha d}e^{-\Delta\beta d}}{\Gamma(n, \infty)}$$

$$F_2 = \frac{e^{-\alpha(2D-d)}e^{-\Delta\beta(2D-d)}}{\Gamma(2N-n, \infty)}$$

$$t_a = t - \frac{d}{u} \qquad t_b = t - \frac{2D-d}{u}$$

$$t_c = t - \frac{d}{u} - t_1 \qquad t_d = t - \frac{2D-a}{u} - t_1$$

$$t_e = t - \frac{d}{u} - t_1 - t_2 \qquad t_f = t - \frac{2D-d}{u} - t_1 - t_2$$

$U(t_a)$ = a step function starting at t_a, etc.,

then,

$$V(t) = \frac{V_s}{2}\Big\{F_1\Big[\Big(t_a - \frac{1}{a}\Big)\Gamma(n, at_a)\frac{U(t_a)}{t_1} - \Big(t_c - \frac{1}{a}\Big)\Big(\frac{1}{t_1}+\frac{1}{t_2}\Big)\Gamma(n, at_c)U(t_c) + \Big(t_e - \frac{1}{a}\Big)\Gamma(n, at_e)\frac{U(t_e)}{t_2}\Big] + F_2\Big[\Big(t_b - \frac{1}{a}\Big)\Gamma(2N-n, at_b)\frac{U(t_b)}{t_1} + \Big(t_d - \frac{1}{a}\Big)\Big(\frac{1}{t_1}+\frac{1}{t_2}\Big)\Gamma(2N-n, at_d)U(t_d) + \Big(t_f - \frac{1}{a}\Big)\Gamma(2N-n, at_f)\frac{U(t_f)}{t_2}\Big]\Big\}, \quad (13)$$

where

n = number of word lines within the distance "d"
N = total number of word lines.

For large scale memories, we should reduce the cross-coupling capacitance between the sense and the word lines. To reduce the capacitance, it is preferable to increase the separation. At the same time, both the sense and the word lines should be close to the magnetic elements to provide adequate coupling.

V. Interconnections

If the conductor is deposited on the substrate by a vacuum process, it has more uniform characteristics than those overlaid on the substrate. For a large-scale memory which consists of an assembly of substrates, we therefore have to interconnect the deposited lines. Interconnection creates discontinuities in the line impedance and causes reflections to the pulses transmitted.

For the sense signal, reflections will cut down the peak and impair the waveform generally. To evaluate the effect, we shall look at the two sense lines of two substrates joined together by another short piece, as shown typically in Fig. 8. Let the impedance of sense line be Z_0 and that of the joint, Z_1'. The resistance of the solder joint r_s is in the order of micro-ohms. We can lump r_s with the impedance Z_1' of the short joining piece, and the corrected value Z_1 is [1]

$$\sqrt{\frac{R_1 + \frac{r_s}{l_1} + j\omega L_1}{G_1 + j\omega C_1}}.$$

For all practical purposes, we can assume that the lines are connected together as shown in Fig. 9. Let the transmission coefficient from

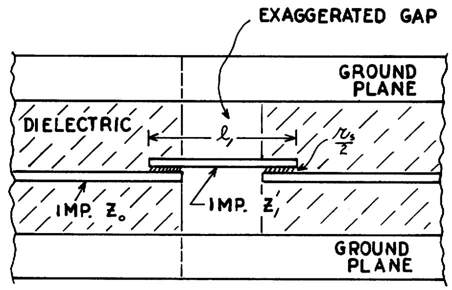

Fig. 8. Interconnecting two sense lines.

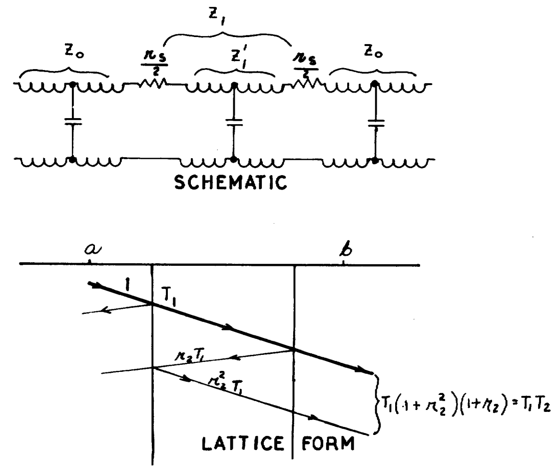

Fig. 9. An equivalent circuit of interconnected lines.

$$Z_0 \text{ to } Z_1 \text{ be } T_1 = \frac{2Z_1}{Z_0 + Z_1}$$

and for a short interconnecting section from

$$Z_1 \text{ to } Z_0 \text{ be } T_2 = \frac{4Z_0(Z_0^2 + Z_1^2)}{(Z_0 + Z_1)^3}.$$

Disregarding the second-order reflections on the main line, we have the ratio of two voltages in the lattice diagram to be

$$T_1T_2.$$

If there are m interconnecting joints, then the total transmission is

$$(T_1T_2)^m.$$

This product of T_1 and T_2 reduces the sense signal and should be kept close to unity. A graph has been prepared in Fig. 10 with the value of T_1T_2 plotted against the ratio of impedance-mismatching ($|Z_1 - Z_0|/Z_0$). It is apparent that the degradation of the signal intensifies as the number of interconnections goes up.

The transmission coefficients are linear. They can be inserted into (13), and we obtain the final expression for the sense signal waveform complete with all the degrading effects discussed above.

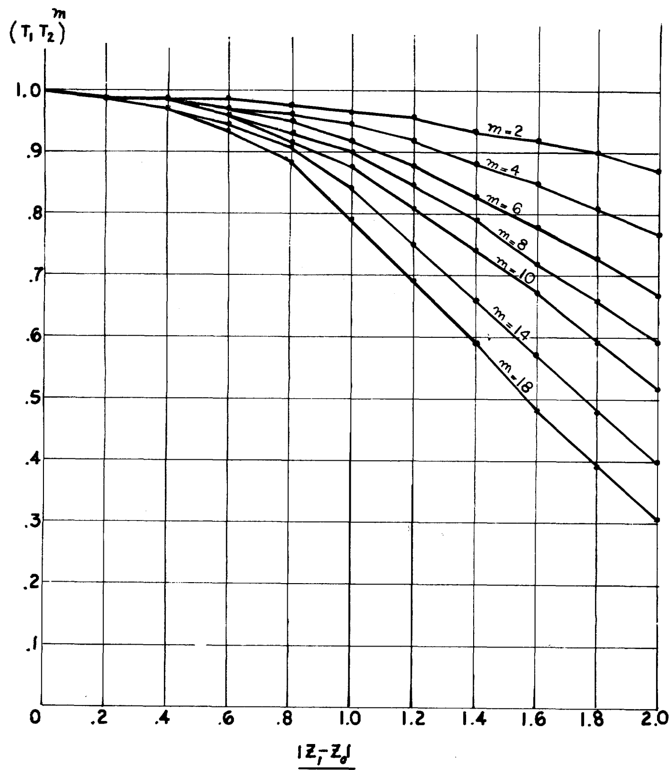

Fig. 10. Transmission vs. impedance-matching.

$$V(t) = \frac{V_s}{2}\Big\{F_1(T_1T_2)^m\Big[\Big(t_a - \frac{1}{a}\Big)\Gamma(n, at_a)\frac{U(t_a)}{t_1} - \Big(t_c - \frac{1}{a}\Big)\Big(\frac{1}{t_1} + \frac{1}{t_2}\Big)\Gamma(n, at_c)U(t_c) + \Big(t_e - \frac{1}{a}\Big)\Gamma(n, at_e)\frac{U(t_e)}{t_2}\Big] + F_2(T_1T_2)^{2M-m}\Big[\Big(t_b - \frac{1}{a}\Big)\Gamma(2N - n, at_b)\frac{U(t_b)}{t_1} - \Big(t^d - \frac{1}{a}\Big)\Big(\frac{1}{t_1} + \frac{1}{t_2}\Big)\Gamma(2N - n, at_d)U(t_d) + \Big(t_f - \frac{1}{a}\Big)\Gamma(2N - n, at_f)\frac{U(t_f)}{t_2}\Big]\Big\}, \quad (14)$$

where

m = number of joints within the distance d
M = total number of joints on one sense line
F's and t's are the same as defined in (13).

The equation is lengthy but it accurately describes the main body of the signal. The high-order reflections would reach the preamplifier at later instants in the form of noise. This is not desirable. A close matching of Z_l and Z_0 will alleviate the problem.

VI. Concluding Discussion

For a good signal-to-noise ratio, the sense amplifier input should maintain a sufficient amplitude with an adequate time duration. To achieve this, we must reduce the degrading effects.

The attenuation term EXP$(-Rd/2Z_0)$ strongly influences the allowable length of the line. To extend the line without unduly attenuating the signal, we should keep the ratio of R to $\sqrt{L/C}$ small. It is not advisable to raise the impedance Z_0 because there would be excessive noise due to the proximity of other lines. The only recourse is the reduction of R.

A conductor deposited by vacuum processes is quite thin, and therefore has relatively high resistance. A copper laminate provides thicker conductors and lower resistance than the deposited lines do, but the overall impedance varies due to manufacturing and assembling tolerances. The lack of uniformity affects the couplings of both driving and sensing fields. A compromise may be reached if deposited lines are reinforced by electroplating to the desired thickness.

When compared with other losses, the effect of distortion is small, because the conductor is not thick in relation to the depth of penetration.

The capacitive couplings of word lines are very disturbing. As indicated in Section IV, the wavefront is degraded by a factor proportional to $C_c \times \sqrt{n}$. To accommodate a large number of word lines, one has to minimize the capacitance at line intersections. The capacitance is equal to dielectric constant×area/separation. Not much can be done in reducing the area because it is dictated by the requirements for the line parameters. A thick insulating layer between the word and sense line is thus preferred.

In view of the reflections, one should avoid the interconnecting of lines. However, if the circumstances demand such interconnection, extreme care is to be exercised to keep the discontinuities as small as possible.

Next, we shall consider the time separation between the two components of the sense signal as shown in (13) or (14). The composite amplitude diminishes as the time separation increases, as shown in Fig. 3, drawn for an ideal line. The worst-case time separation is the time for one round trip on the line. Therefore, for long lines, high magnetic film output signals are needed. The only advantage of signal attenuation is that it helps to make the signals less irregular in magnitude at the sensing terminal.

A computer program was used to evaluate (14). The ratio of incomplete Gamma function to factorial function is replaced by [11]

$$1 - \sum_{n=0}^{n-1} \frac{(at)^n}{n!} e^{-at}.$$

Only terms up to Kth are included where

$$\left|\frac{(at)^{K+1}}{(K+1)!}\right| < \epsilon,$$

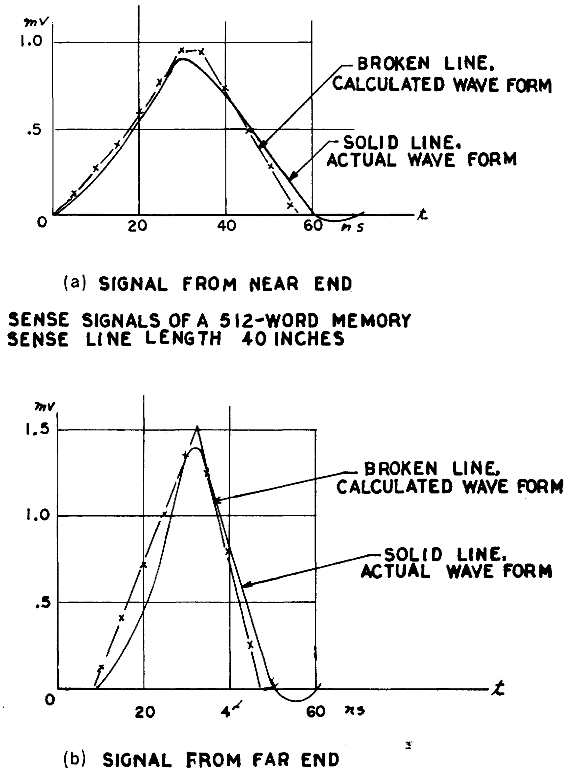

Fig. 11. Sense signals on an actual line.

ϵ is a prescribed error. The signals plotted with the data from the computations generally agree with the experiments, as shown in Fig. 11.

Although the sense signal will merge with the cross-talk, the feeding-through "Read" current and other noise, no attempt has been made to examine any one of them. They merit treatises in their own right.

This paper has discussed the propagation of sense signals as a design guide to the sense line. Being an integral part of a memory stack, the sense line plays an important role in the overall planning of a memory. A successful design of the memory, in turn, will require careful consideration of all aspects and reach a balance among them.

Appendix I

The dc resistance of a conductor, W units wide and b units thick, is

$$R_{\text{dc}} = \frac{1}{Wb\sigma} \text{ per unit length}$$

and the high-frequency resistance

$$R = \frac{1}{W\sigma\delta}\left[\frac{\operatorname{Sinh}\dfrac{2b}{\delta} + \operatorname{Sin}\dfrac{2b}{\delta}}{\operatorname{Cosh}\dfrac{2b}{\delta} - \operatorname{Cos}\dfrac{2b}{\delta}}\right]$$

$$= \frac{1}{W\sigma\delta} \times K$$

$$= R_{\text{dc}}\frac{bK}{\delta} = R_{\text{dc}}\left[1 + \frac{bK - \delta}{\delta}\right]$$

$$= R_{\text{dc}}[1 + \eta] \text{ per unit length.}$$

Appendix II

$$\mathcal{L}^{-1}\frac{a^n}{P^2(P+a)^n}$$

$$= a^n \int_0^t \frac{\tau^{n-1}}{(n-1)!} e^{-a\tau}(t-\tau)\, d\tau$$

$$= \frac{a^n}{(n-1)!}\left[\frac{t}{a}\int_0^{at} \frac{(a\tau)^{n-1}}{a^{n-1}} e^{-a\tau}\, d(a\tau) - \frac{1}{a}\int_0^{at} \frac{(a\tau)^n}{a^n} e^{-a\tau}\, d(a\tau)\right]$$

$$= \frac{a^n}{(n-1)!}\left[\frac{t}{a^n}\Gamma(n-1, at) - \frac{t}{a^{n+1}}\Gamma(n, at)\right]$$

$$= \frac{t}{(n-1)!}\Gamma(n-1, at) - \frac{1}{a(n-1)!}\Gamma(n, at)\Big].$$

For large n,

$$\mathcal{L}^{-1}\frac{a^n}{P^2(P+a)^n} \approx \left(t - \frac{1}{a}\right)\frac{\Gamma(n, at)}{\Gamma(n, \infty)}.$$

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