IRE Transactions on AUDIO

Volume AU-8 MARCH-APRIL, 1960 Number 2

Published Bi-Monthly

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PUBLISHED BY THE
Professional Group on Audio

World Radio History

IRE PROFESSIONAL GROUP ON AUDIO

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Cincinnati, Ohio

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Armour Research Foundation
Chicago 16, Ill.

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Editorial Committee

Marvin Camras, *Editor*
Armour Research Foundation, Chicago 16, Ill.

B. B. Bauer
CBS Laboratories
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The Editor's Corner

Magnetic Recording for Home Entertainment

THIS magnetic recording issue of TRANSACTIONS brings to mind some historical "audio plans" for magnetic recorders. In its first fifty years magnetic recording never was a serious rival to the disk phonograph for prerecorded music. But fifteen years ago magnetic recording seemed unique in its ability to provide uninterrupted, long playing, high quality sound, as compared to 78-rpm disks which had to be changed every five minutes. Here, at last, was an ideal medium for "serious" music.

Plans along this line were set back when the LP record came into its own. Television also made its debut, using up the consumer's dollar, and also his spare time, so there wasn't much of either left for magnetic recording.

The mid-Fifties brought a renaissance in the recorded classics through the magic words "high-fidelity." High-fidelity enthusiasts, always looking for something better, discovered stereophonic sound. Magnetic tape recording was the only practical medium for stereo, and its future seemed assured. Then came stereo-disk and another setback for magnetic recording.

Magnetic recording is no longer unique for long playing nor for stereo. Does it have any exclusive features left? There are quite a few. Tape recording has the reputation for superior fidelity, which is retained throughout a practically unlimited life. Tape furnishes three or more channels for enhanced stereo, and even with two channels it gives better separation and lower distortion than disks. Tape cartridges are rugged, in contrast to delicate disk surfaces. They are more compact, easier to store, and easier to use. A cartridge changer gives many hours of unattended programming. The erase feature allows interesting possibilities for the sale of music, separately from the cartridge, by vending machines where one could insert an unrecorded cartridge and select the music to be recorded.

An important problem has been cost. In the past we did not use tape economically. Recently, by recording more tracks across the tape, and by operating at slower speed, the basic cost has been reduced to a point where tape can compete in price with LP phonograph records.

There is a danger of carrying economy too far, and slowing the speed to a point where low-cost mass-produced machines cannot maintain good quality of sound. Even in the phonograph industry where problems are less severe, the most common defect is excessive wow and rumble.

In the next few years recorded tape music may be commonplace. Let us hope that it will bring uncommonly excellent audio quality.

—Marvin Camras, *Editor*

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PGA News

CHAPTER NEWS

Houston, Texas

Mr. H. B. Balch of B&M Electronic Service spoke on "The Mechanics of Tape Recording" on January 19, 1960.

Cleveland, Ohio

Ralph Delany, Chief Engineer, WHK, Cleveland, Ohio, has become Chairman of the Cleveland Chapter, PGA.

RECORDING SUPERVISOR CONFERENCE

(TONMEISTERTAGUNG)

The North West German Music Academy in Detmold intends, once again, to hold a Recording Supervisor Conference from October 18–21, 1960, in Detmold, Germany. Persons who are interested in problems of electroacoustic recording and reproduction from both the artistic and the technical point of view are cordially invited.

As in the previous conferences in 1949, 1951, 1954 and 1957, the subjects to be discussed will be grouped around two main themes. The first group will contain subjects taken from the fields of art and music sciences, musical interpretation, physiological acoustics, and sound psychology. In the second group, lectures will be given on physical and technological aspects of microphones, loudspeakers, recordings, level indication and control, studio techniques, architectural acoustics, etc. Papers on these themes and especially any on the interrelationship between musical and technological spheres are welcome.

Again, the focus of the techical discussions will be stereophony. This topic promises to be interesting since the problem of stereophonic disk recording has been solved technically and the exchange of information concerning recent activity should be most valuable.

In addition to the reports, special interest is attached to demonstrations of recordings of all kinds, including electronic methods of sound transformation such as the stylizing of sounds and noises for musical and sound effects underlying radio plays, movies, or stage performances.

All persons interested in submitting papers are requested to inform, as soon as possible, Prof. Dr. E. Thienhaus, Nordwestdeutsche Musik-Akademie, Detmold, Germany, as to the subject and length of the paper. The final date for submission of papers is June, 1960. Participants should register with the secretary of Nordwestdeutsche Musik-Akademie, Detmold, Germany.

PGA ELECTION RESULTS ANNOUNCED

The results of PGA's recent election have been announced as follows: Hugh Knowles is the new Chairman of the Administrative Committee, and P. C. Goldmark, the new Vice-Chairman. Michel Copel, C. M. Harris, and R. W. Benson have been elected to the Administrative Committee.

Winners of the 1959 PGA Awards are as follows:

A. B. Bereskin and P. C. Goldmark—Achievement Award
H. K. Dunn—Senior Award
J. S. Aagard—Papers Award.

Full details on the new officers and the award winners will appear in the May–June issue.

A Comparison of Several Methods of Measuring Noise in Magnetic Recorders for Audio Applications*

JOHN G. McKNIGHT†

Summary.—The various methods of measuring noise in audio magnetic recorders are discussed, and data are shown comparing the numbers observed for the different methods (IRE Standard Methods, and others) when applied to the same recorder. This data will enable one to compare other data taken by one method with data taken by another method.

The present audio specifications based only on broad-band noise are shown to be inadequate, as the equipment noise in the range of low hearing sensitivity masks any improvements which may be made in tape noise, or with the Ampex Master Equalization. A measure of relative audible noise level should be added to the present broad-band measurement.

INTRODUCTION

SEVERAL methods are used to measure the noise level in magnetic recorders for audio applications. Some of these methods have the status of standards; other methods are used because they are more simply applied or more appropriate to the test equipment at hand. We will discuss the various methods, and their advantages and disadvantages, and compare the results of the different methods when used to measure the same magnetic recorder.

DEFINITIONS[1]

A noise measurement must be referred to something. We will take as reference the vu meter zero level, which is the "operating level" on the standard tape, and is nominally the 1 per cent distortion level of the tape.[2]

The "noise" may be a noise spectrum, unweighted high-frequency noise, broad-band noise, or weighted noise. These will be defined and discussed below. We also need to know what part of the system is generating the noise, and so we define the following: "system noise"—"the noise output which . . . is generated by the system or any of its components, *including the medium*"; "equipment noise"—"that . . . which is contributed by the . . . equipment during recording and reproduction, *excluding the medium* . . . "; and "medium noise"—"that noise which can be specifically ascribed to the medium."

This paper deals only with "zero-modulation medium noise"—"that noise which is developed in the . . . reproducing process when the medium is . . . in . . . the state of complete preparation for playback . . . except for omission of the recording signal: magnetic recording media . . . subjected to normal erase, and bias . . . fields characteristic of the . . . system with no recording signal applied." "Modulation noise"—" . . . which exists only in the presence of a signal and is a function of the instantaneous amplitude of the recorded signal"—will not be discussed here.

All data shown were taken with average reading meters, not true rms meters. This is permitted in the standards.

NOISE MEASURING METHODS

All data below are for an Ampex Model 351 recorder, one-quarter inch full-track, 15-ips, NAB equalization, Irish 211 tape, biased to "peak" at 15-mil wavelength. Reference level is the "operating level" of the Ampex 4494 standard alignment tape (nominal 1 per cent distortion level).

Noise Spectrum Analysis

"The noise spectrum may be analyzed by . . . a very narrow bandpass filter of variable frequency. . . . The results, in terms of power, are divided by the equivalent bandwidth . . . of the filter at each test frequency."

This analysis may be either by a wave analyzer or by a one-half or one-third octave band filter. A wave analyzer is inherently a "constant bandwidth" device; therefore, the data need be corrected only by a constant correction (in db) = 10 log bandwidth (in cycles). Fig. 1 shows the data from a HP 302A wave analyzer, with the noise energy as read (7-c bandwidth) and for noise energy per cycle ($8\frac{1}{2}$-db correction added). Readings with a wave analyzer of narrow bandwidth (such as the HP 302A) are directly usable, but have the difficulty of involving an expensive unit; and the meter reading fluctuates greatly (due to the narrow bandwith) and must either be "eye-ball" averaged or have a large condenser shunted across the meter to average the reading.

Fig. 2 shows the data from a Bruel and Kjaer Spectrometer, a constant percentage ($\frac{1}{3}$ octave) filter. Since these data are in energy per one-third octave, they must be reduced to "energy per cycle" form. The correction to be applied at each frequency (in db) is $10 \log \Delta f$, where Δf is

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* Manuscript received by the PGA, November 19, 1959.

† Advanced Audio Section, Ampex Professional Products Co., Redwood City, Calif.

[1] The definitions in quotations are abridged from "Standards on sound recording and reproducing, methods of measurement of noise," PROC. IRE, vol. 41, pp. 508–512; April 1953. (Standard 53-IRE 19-S-1.)

[2] Various other choices for reference level are discussed in J. G. McKnight, "Signal-to-noise problems and a new equalization for magnetic recording of music," *J. AES*, vol. 7, pp. 5–12; January, 1959. See especially pp. 6–8 on "signal measurement."

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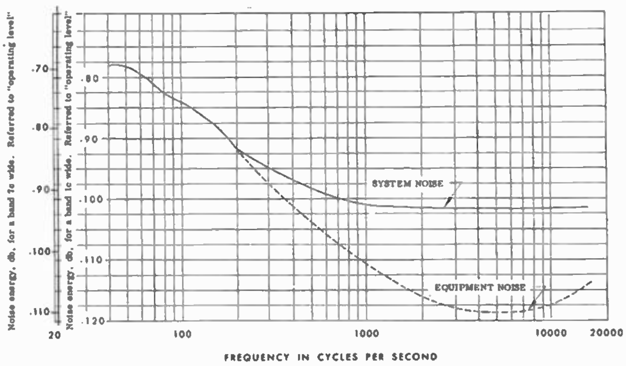

Fig. 1—Noise spectrum analysis. HP 302A wave analyzer, 7-c constand bandwidth. Ampex Model 351, one-quarter inch full-track, 15-ips, NAB equalization. Irish 211 tape, biased to "peak" at 15-mil recorded wavelength.

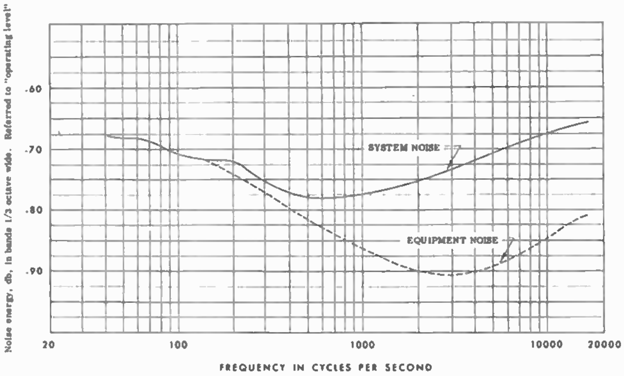

Fig. 2—Noise spectrum analysis. Bruel and Kjaer Spectrometer, one-third octave constant per cent bandwidth. Ampex Model 351, one-quarter inch full-track, 15-ips, NAB equalization. Irish 211 tape, biased to "peak" at 15-mil recorded wavelength.

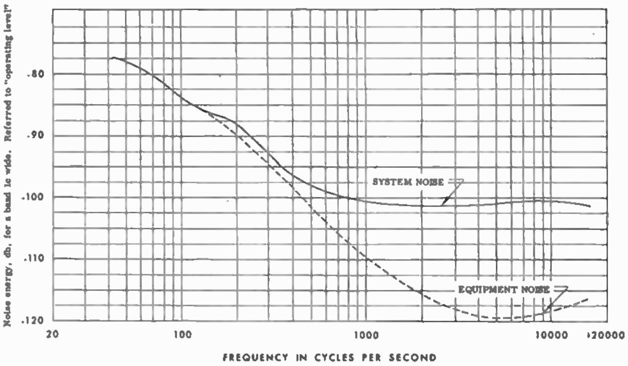

Fig. 3—Noise spectrum analysis. Bruel and Kjaer Spectrometer, one-third octave constant per cent bandwidth. Data converted to constant bandwidth (1c) form. Ampex Model 351, one-quarter inch full-track, 15-ips, NAB equalization. Irish 211 tape, biased to "peak" at 15-mil recorded wavelength.

the bandwidth, in cycles, of any band. Fig. 3 shows these data as corrected; this transforms the curve to the same curve as Fig. 1, from the wave analyzer, proving that the two methods are identical in result. The same advantages and disadvantages apply as for the wave analyzer, except that the correction is a function of frequency instead of a constant.

The noise spectrum analysis gives the most complete data on noise. It shows the actual amount of noise vs frequency; by measuring system noise and equipment noise, one can quickly determine whether the equipment noise is adequately below the medium noise. Single frequency components (such as hum) must be treated separately, and have not been discussed in this paper. To interpret *audible* noise level, one must compare the noise spectrum shape to the appropriate equal loudness curve for the ear.

Broadband Noise Measurements

For broadband noise measurement, a sensitive voltmeter is connected across the equipment output terminals. The only precaution is to be sure to avoid reading any bias frequency which may be present in the "record" mode. Bias may be eliminated either by playing back separately after record (instead of during record) or by using a filter to eliminate the bias (but not to attenuate the pass band). This method gives a system noise of $-53\frac{1}{2}$ db and an equipment noise of -56 db.

This measurement requires the least equipment and provides the least useful data. It is adequate for simple quality control purposes, as the measuring equipment is relatively inexpensive and a single number limit may be set on allowable noise. However, this scheme is inadequate for evaluation of the medium (tape) noise, since (as can be seen in the spectrum analysis of Fig. 1) the medium noise is completely masked by equipment noise below 300 c. Also, any increase in the system noise in the 3-kc region (where the ear is most sensitive) would be masked by the low-frequency noise.

The reading will, of course, depend upon the bandwidth of the "broad band." Equipment specifications should include the band to be used. Fig. 4, (a) and (b) shows the effect of inserting a high- or low-pass filter between the equipment output and the meter. These also point out the fact that the equipment noise largely controls the reading at low frequencies.

Unweighted High-Frequency Noise Measurements

"A 250 c high-pass filter . . . is connected between the . . . equipment and the . . . measuring device. All measurements . . . may be repeated to obtain the signal-to-noise ratio corresponding to the portion of the spectrum which is essentially free of the low-frequency vacuum tube 'flicker' noise of the playback preamplifier input stage and hum of the power-line frequency and its major harmonics." The readings for a bandpass of 250 c to 16,500 c [as could also have been read from Fig. 4(b)] are system noise of -57 db and equipment noise of -68 db.

This method has the simplicity of the broad-band method, with the advantage of showing up differences in medium noise or equipment noise in the 3-kc region, but the disadvantage of not indicating possible low-frequency hum and noise.

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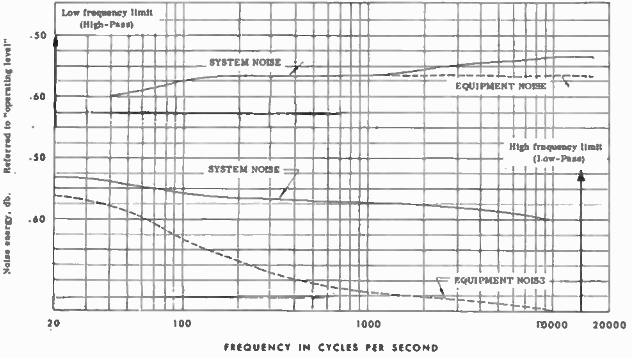

Fig. 4—Cumulative noise. "Broad-band" noise restricted by high- or low-pass filter. SKL Model 302 filter (18-db octave). HP 400L voltmeter. Ampex Model 351, one-quarter inch full-track, 15-ips, NAB equalization. Irish 211 tape, biased to "peak" at 15-mil recorded wavelength. (a) Variable low pass—noise below frequency. (b) Variable high pass—noise above frequency.

A nonstandard variation of this method has been to use 1-kc to 5-kc unweighted high-frequency noise measurement. This gives a system noise of −64 db and an equipment noise of −75 db. The medium noise is seen to be 7 db less than for the 250-c to 16,500-c bandpass (−57 db vs −64 db); equipment noise is also reduced by 7 db (−68 db vs −75 db). This might be desirable when making measurements on the medium itself, where the high-frequency noise is of primary importance and the possibility exists of having a medium whose noise spectrum may approach that of the equipment in the 3-kc region.

Weighted Noise Measurement

"Appropriate contour curves may be used as a basis for establishing a weighted response . . . if it is desired to relate the data to the hearing characteristic." A response similar to the ASA "A" weighting curve is appropriate.[3] The Bruel and Kjaer Spectrometer contains an "A" weighting curve; or a very simple circuit can be used, as shown in Fig. 5. The B and K "A" network gives system noise of −62 db, equipment noise of −71½ db.

The network in Fig. 5 is more similar to the ear curves than the response established by the ASA (this network is still within ASA tolerances) and gives system noise of −58½ db and equipment noise of −72½ db. This network is seen to have a response roughly similar to the filters used for unweighted high-frequency noise measurement, and gives similar results.

The weighting network has the same advantages (readings are proportional to audible noise and equipment is simple and inexpensive) and disadvantages (hum and low-frequency noise are not indicated unless very large) as the unweighted high-frequency noise measurement, with the additional advantage of being much less expensive than a band-pass filter.

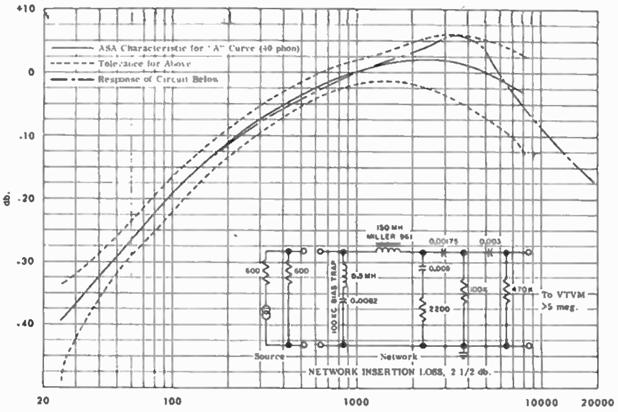

Fig. 5—Response-frequency characteristics and circuit of network for objective noise measurement.

COMPARISON TABLE

Table I is compiled from the data discussed above and is presented so that data taken in the different forms may be compared. All data are for an Ampex Model 351 recorder, one-quarter inch full-track, 15-ips, NAB equalization, Irish 211 tape, biased to "peak." Reference level for all measurements is the "operating level" of the Ampex 4494 standard alignment tape (nominal 1 per cent distortion level).

TABLE I

Type of Measurement	System Noise, Decibels Below Operating Level	Equipment Noise, Decibels Below Operating Level
Noise spectrum data at 3 kc:		
Uncorrected data		
HP 302A (7-c bandwidth)	93	110
B&K Spectrometer (⅓ octave)	73	93
Corrected data, energy/cycle (HP or B&K)	101½	118½
Broadband: (no response limiting filter used)	53½	56
Unweighted high frequency:		
250 c–16 kc	57	68
1 kc–5 kc	64	75
Weighted: B&K "A" weighting	62	71½
Network, Fig. 5	58½	72½

CONCLUSION

A noise spectrum analysis gives complete data necessary for evaluation of the system, equipment, and medium noise, but the measuring equipment (a wave analyzer, or one-half or one-third octave filter) is expensive, data-taking is somewhat time consuming, simple data corrections are necessary, and interpretation of the data requires some skill.

The broad-band noise measurement is very simple, but the data tell little except that there is probably no gross defect of the system.

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[3] *Ibid.*, pp. 8–9, on "noise measurement."

Unweighted high-frequency noise measurement, and weighted noise measurement both give a good indication of the relative "noisiness" as judged by the ear, but may not indicate low-frequency hum or noise unless they are extreme. It is suggested that, for audio magnetic recording equipment, specifications and quality control methods be based on broad-band noise measurements (as presently used) to indicate low-frequency hum and noise, plus either unweighted high-frequency noise or weighted noise measurement to indicate the relative audible noise level.

The addition of this "relative audible noise level" measurement is also desirable because of our development of new, lower noise systems (the Ampex Master Equalization) which show no improvement in broadband noise, due to the low frequency equipment noise.

For measuring the noise of the medium, the unweighted high frequency, or "A" weighted readings or one-third octave at 3 kc are equally valid. Use of the unweighted high-frequency noise (either bandpass) is the simplest standard method using standard lab equipment. Use of the "A" weighting network in Fig. 5 is the very simplest standard method, if one is willing to construct the network.

Magnetic Recording and Reproduction of Pulses*

DONALD F. ELDRIDGE†

Summary—The most widely used techniques for recording digital information on a moving magnetic medium are return-to-zero (RZ) and non-return-to-zero (NRZ). Both techniques have some peculiar advantages and disadvantages. Although sophisticated coding methods may be utilized to increase information density, the density achievable by any method is determined by the basic resolution of the record and reproduce processes.

An expression is derived for the output of a reproduce head when an ideally recorded pulse is passed over it. The output is a function of the head fringing field in the region occupied by the recorded medium, and is the sum of the outputs produced by the longitudinal and perpendicular components of magnetization. A novel technique is used to measure the relative magnitudes of the components in a typical saturated recording tape. The perpendicular component is 11 per cent of the longitudinal component and may be neglected for the practical case.

From a combination of experimental and theoretical data the width and height of the reproduced pulse are computed for variable gap width, medium thickness, and head-to-medium spacing. The effect of a nonideal pulse with a finite recorded width is considered. The total output pulse width is shown to be the sum of the computed ideal reproduce pulse width and the width of the actual recorded pulse. From the curves presented, one may observe that only a slight increase in resolution can be achieved by utilizing very small reproduce head gaps.

Data are presented on the measured initial magnetization characteristics of a typical oxide. The characteristic may be approximated by either an offset linear curve up to about 60 per cent of saturation or a fourth power curve up to about 30 per cent of saturation. Data are also presented to show the effect of previous magnetization upon the transfer characteristic.

The record process is analyzed with a step-by-step technique utilizing measured data on the head field and oxide magnetization characteristics. It is shown that both the shape and location of the recorded pulse are functions of the medium magnetization characteristic, the record head gap width, the record current, the medium thickness, and the head-to-medium spacing. The effect of each of these variables is computed. The computed results are verified experimentally. It is shown that under a wide range of conditions the reproduce pulse width obtained from a given head is approximately five times the width of a pulse ideally recorded by the same head. It is further shown that when the spacing between head and medium is larger than the gap width, the resulting over-all reproduced pulse width is approximately seven times the head-to-medium spacing.

Previous recording history of the medium has a significant effect upon the pulse location. Data presented indicate that the record current must be approximately twice the current required for medium saturation to make the pulse location error unmeasurable.

INTRODUCTION

IN the type of recording investigated here, a step function—usually between equal values of opposite polarity—is recorded upon the tape. When the tape is passed over a reproduce head, the resulting voltage is ideally the time derivative of the tape magnetization with one pulse for each step change. In practice, one cannot record a perfect step function, nor can the reproduce head produce an exact derivative of the tape magnetization. The amplitude, shape, duration, and location of the recorded and reproduced pulses will be functions of the record and reproduce head geometry, the spacing of the tape away from the heads, the record field amplitude, and the tape magnetization characteristics and previous history.

If one is to achieve maximum recorded information density and accuracy, the factors influencing pulse width, height, shape, and location must be understood and considered. The purpose of this study was to investigate and define the influence of as many of these factors as possible. Where possible, both theoretical and experimental analyses were made and compared. The reproduce and record processes are treated separately in the order mentioned.

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* Manuscript received by the PGA, August 28, 1959.

† Res. Div., Ampex Corp., Redwood City, Calif.

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DIGITAL RECORDING

The major difference between digital and the various forms of analog recording (direct, FM, pwm, etc.) is that the information is converted to—or already exists in—numerical form before recording.

The binary system is used almost exclusively because of its simplicity and reliability. With the binary system, only two states need be recorded and reproduced—a state representing a "1" and the other representing a "0." The two states might be in the form of different amplitudes, frequencies, time durations, shapes, polarities, etc., or the presence or absence of one of these. The more common systems will be discussed briefly.

Return-to-Zero (RZ) Recording

An unmagnetized medium is recorded upon by passing short current pulses of either polarity through a record head. During reproduction, a pulse is reproduced for each recorded bit, and the polarity determines its numerical value (see Fig. 1). The recording of a pulse for each bit has the advantage that a lack of signal is obviously an error, and that it is easy to detect the pulses at the right instant. In addition, a dropout which lifts the recording medium away from either the record or reproduce head will produce no error in the location of the pulse along the medium. Also, the average record current is small. The disadvantages are that the medium must be erased prior to recording or the exact location of prerecorded information must be known, and dropouts will produce a considerable loss in reproduce amplitude because all recording is done at short effective wavelengths.

Non-Return-to-Zero (NRZ) Recording

In NRZ recording, the medium is magnetized to saturation of either polarity at all times. Information is recorded in the form of polarity reversals which are differentiated by the reproduce head to produce pulses of both polarities (see Fig. 2). A reversal may represent a binary "1," and the lack of same a binary "0." A reversal may also represent a change from "1's" to "0's," or various other codings may be used. The advantages of NRZ recording are that dropouts which space the medium away from the heads will produce less amplitude drop than in RZ recording at low and medium packing densities (pulses per inch) because the effective wavelengths are long. However, such dropouts during the record process will produce a shift in the location of the pulse along the medium. Also, since recording is done at saturation, the medium need not be erased prior to use. When recording on a previously magnetized medium, the record field (or current) required to obliterate the previous recording is approximately twice that which would be required to saturate an initially unmagnetized medium.

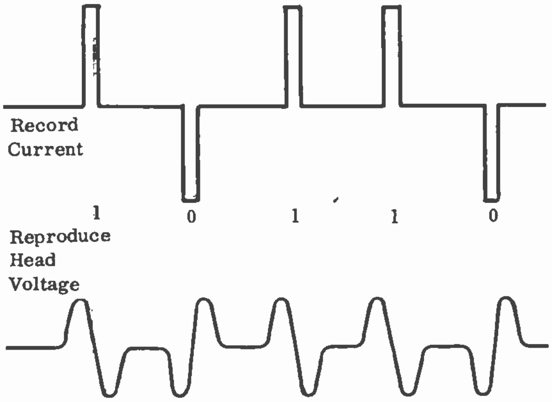

Fig. 1—RZ recording waveforms.

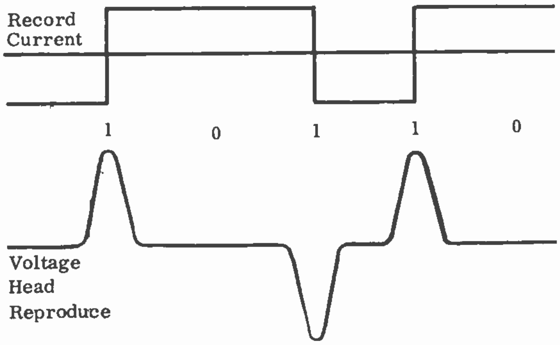

Fig. 2—NRZ recording waveforms.

It has been assumed by some that NRZ recording is inherently capable of twice the information density of RZ recording, because head current is switched once per bit (say from plus to minus) in NRZ and twice per bit (OFF-ON and ON-OFF) in RZ recording. The fallacy in this reasoning is apparent when one examines the reproduced pulse widths produced with both systems. The widths are very nearly identical; hence, the packing densities obtainable are approximately the same. Some difference is observed when the record current is increased above saturation. The RZ pulse becomes wider than the NRZ pulse at the same record current. The major disadvantage of NRZ recording is that information may be in the form of an absence of a pulse. This necessitates some external means of determining when to sample a particular channel for the presence or absence of signal. On a multitrack tape machine, one or two tracks may be used as "clocks," with a reversal being recorded during every bit interval. When a pulse appears on the clock track(s), all other tracks are sampled. As all tracks must be read out simultaneously, intertrack errors caused by mechanical misalignments and differences in time of detection become very important, and will limit the packing density to a value which may be much lower than that determined by head resolution alone.

Another difficulty arises because it is impossible to discriminate between a lack of signal which is intentional and one which is caused by a dropout or other malfunction, with simple detection schemes. Tape noise is at a maximum in NRZ recording because the medium is saturated in the intervals between pulses. NRZ record-

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ing has the highest power requirement of any recording method because full saturation current must flow in the record heads at all times during recording.

Presaturation Recording

The medium may be prepared by saturating it in one direction prior to recording by placing a permanent magnet head just preceding the record head. Information may then be recorded in a manner similar to normal NRZ, or in short pulses. This method has an advantage over normal NRZ in that only half the average record power is required. Record current may further be reduced if the permanent magnetic head field is made sufficiently strong to obliterate completely previous magnetization of the medium. And, as the total flux switched during the record process is less, magnetic crosstalk will be reduced.

When short pulses are recorded by this method, the total flux change in the medium is twice that possible with RZ recording. However, only a single polarity pulse may be recorded.

Plane of Recording

Any of the preceding recording methods may be used for recording in any of the three planes of the medium. Longitudinal recording (magnetization in the direction of medium motion) is most commonly used with tape. Perpendicular and longitudinal recording are both used in fixed-medium devices such as drums and disks. It has been proposed that perpendicular recording be used with tape for increased dropout reliability. The bit packing density possible with this system is relatively low because of the large spacing between head poles. At low packing densities, large gap longitudinal heads would provide the same reliability with less complexity of construction and operation.

Transverse recording (magnetization across the medium at 90° to the direction of motion) is rarely used because track width is determined by gap width. With a normal width track, very poor resolution would result. This method might become desirable if very narrow tracks were to be used.

Packing Density

In straightforward RZ or NRZ recording, the maximum bit packing density is usually defined as the density (in pulses per inch) where adjacent pulses start to overlap at some arbitrary base point. This base point might range from 5 to 30 per cent of peak pulse amplitude. In practice, considerably greater packing densities may be realized with sophistication in the recorded code and in the code detection devices. The phase, slope, amplitude, and duration of pulses may be modulated to produce reliable binary recording even with considerable overlap between adjacent pulses. In the detection circuits, both integration and differentiation of the signal can enhance the packing density. Logical circuitry and correlation techniques can further increase maximum density. With any particular modulation and detection system, the maximum packing density will be a function of the actual width of a single reproduced pulse. This width is determined by the characteristics of the record and reproduce heads and the magnetic medium. Most of the work included in this report is directed toward analyzing the factors which influence the width of a single NRZ pulse. NRZ was chosen because it is in most general use. Most of the analysis techniques and much of the information presented also apply to RZ recording.

THE REPRODUCTION PROCESS

Derivation of the Reproduce-Head Output

In order to determine the effects of the various parameters on the output pulse, a general relationship between the voltage pulse and the physical factors involved must first be established. This relationship will be derived for a single perfectly recorded step change in magnetization M from $-m$ to $+m$. Later, the effect of finite length of the recorded step will be considered. It will be assumed, for the time being, that M is uniform throughout the depth of the magnetic medium, and that the change from $-m$ to $+m$ occurs in zero length along the tape. (The actual shape of the recorded signal will be considered in the analysis of the record process.)

Further assumptions will be that the permeability of the reproduce head is infinite, the permeability of the medium is unity, and that the effects of finite tape width may be neglected. Gilbert[1] has derived the general expression for the flux through the pickup coil as

$$\phi = K \iint M \cdot H dy dx \tag{1}$$

where M is the magnetization of the tape and H is the field outside the head which would be produced by a current passing through the pickup coil. Westmijze[2] has derived a special case for sinusoidal magnetization in the x direction and zero magnetization in the y and z directions. The total flux ϕ may be expressed as $\phi = \phi_x + \phi_y$, where ϕ_x is produced by the horizontal component of magnetization M_x and ϕ_y is produced by the vertical component M_y. Then

$$\phi = \phi_x + \phi_y = K \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M_x \cdot H_x dy dx$$
$$+ K \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M_y \cdot H_y dy dx.$$

Consider first the integral with respect to dx. In Fig. 3, the y axis is on the gap centerline, the x axis is on the head surface, and $\bar{x}$ is the distance of the step change from the gap centerline. Fig. 4 illustrates the shape of the H_x and H_y functions at one value of y for a head with a small gap and pole pieces extending to infinity.

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[1] T. L. Gilbert, "Theoretical Aspects of Noise in Magnetic Recorders," Armour Res. Foundation Bull. No. 94, pp. 43–73; 1956.

[2] W. K. Westmijze, Phillips Res. Rept. No. 8; 1953.

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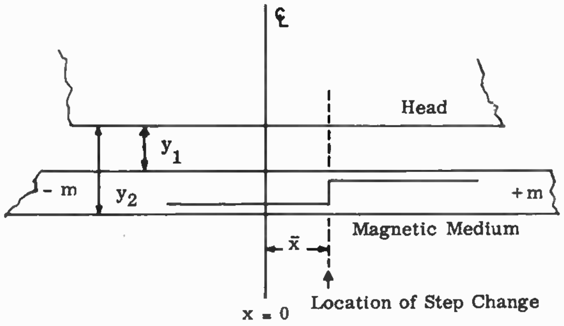

Fig. 3—Ideal recorded step function passing reproduce head.

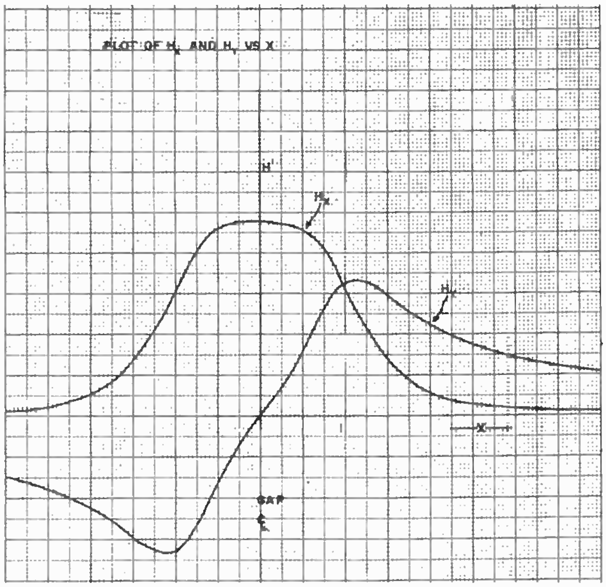

Fig. 4—Field distribution of a gap-type head.

The integral

$$\int_{-\infty}^{\infty} M_x \cdot H_x d_x$$

may be written as the sum of integrals over several values of x from $-\infty$ to $+\infty$, namely:

$$\int_{-\infty}^{\infty} M_x \cdot H_x d_x = \int_{-\infty}^{-|\bar{x}|} M_x \cdot H_x d_x + \int_{-|x|}^{0} M_x \cdot H_x d_x + \int_{0}^{|\bar{x}|} M_x \cdot H_x d_x + \int_{|x|}^{\infty} M_x \cdot H_x d_x.$$

Since $M_x = -m_x$ in the region $-\infty < x < |\bar{x}|$ and $M_x = +m_x$ in the region $|\bar{x}| < x < \infty$, the preceding integrals may be written as

$$\int_{-\infty}^{\infty} M_x \cdot H_x dx = m_x \left[-\int_{-\infty}^{-|\bar{x}|} H_x dx - \int_{-|x|}^{0} H_x dx - \int_{0}^{|\bar{x}|} H_x dx + \int_{|\bar{x}|}^{\infty} H_x dx \right]. \quad (2)$$

Since, because of symmetry, $H_x(x) = H_x(-x)$, then

$$\int_{-\infty}^{-|\bar{x}|} H_x dx = \int_{|\bar{x}|}^{\infty} H_x dx \text{ and } \int_{-|x|}^{0} H_x dx = \int_{0}^{|\bar{x}|} H_x dx.$$

Hence, the first and fourth integrals inside the brackets in (2) cancel out and the second and third integrals add, so that the integrals reduces to

$$\int_{-\infty}^{\infty} M_x \cdot H_x dx = -2m_x \int_{0}^{|\bar{x}|} H_x dx. \quad (3)$$

In a similar manner it may be shown that

$$\int_{-\infty}^{\infty} M_y \cdot H_y dx = -2m_y \int_{0}^{|\bar{x}|} H_y dx. \quad (4)$$

We may now obtain an expression for the voltage as a function of $\bar{x}$. The instantaneous voltage is

$$e = -10^{-8} N \frac{d\phi}{dt} = -10^{-8} N \frac{d\phi}{d\bar{x}} \frac{d\bar{x}}{dt} = -10^{-8} N v \frac{d\phi}{d\bar{x}}$$

and the voltage per unit velocity is

$$\frac{e}{v} = -10^{-8} N \frac{d\phi}{dx} \cdot$$

When we substitute (3) into (1) and differentiate with respect to $\bar{x}$, we have

$$\frac{d\phi}{d\bar{x}} = -\frac{d}{d\bar{x}} \cdot 2m_x K \int_{0}^{|\bar{x}|} \int_{-\infty}^{\infty} H_x dy dx = -2m_x K \int_{-\infty}^{\infty} H_x dy.$$

Since M_x is equal to zero except for

$$y_1 \overline{<} y \overline{<} y_2, \quad \frac{d\phi}{d\bar{x}} = -2m_x K \int_{y_1}^{y_2} H_x dy,$$

and

$$\frac{e_x}{v} = (2) 10^{-8} m_x N K \int_{y_1}^{y_2} H_x dy = m_x K \int_{y_1}^{y_2} H_x dy. \quad (5)$$

Similarly,

$$\frac{e_y}{v} = m_y K \int_{y_1}^{y_2} H_y dy. \quad (6)$$

This shows that the output pulse, as a function of $\bar{x}$, will be identical in shape with the integral of the head-fringing field over the region occupied by the magnetic medium. Hoagland[3] has derived a similar expression, using reciprocity, for the case of an infinitely thin medium, $e(\bar{x})/v = F(H_x)$. With (5), we may investigate the effects on the reproduce process of gap size, tape thickness, and head-to-tape spacing for conventional heads and for heads of unusual design.

Horizontal and Vertical Components of M

The total output voltage is the sum of the voltages produced by the horizontal and vertical components of magnetization. To make use of the above equations, therefore, we must have some idea of the relative values of m_x and m_y. A technique was devised for measuring

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[3] A. S. Hoagland, "Magnetic data recording theory: head design," *Commun. and Electronics*; November, 1956.

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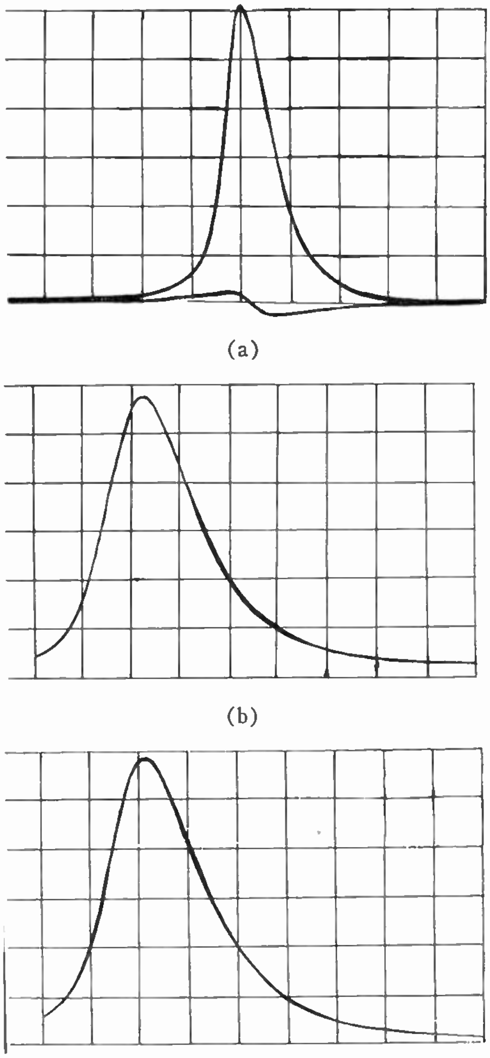
these values and measurements were made at approximately tape-saturation level. From Fig. 4 we see that H_x is positive on both sides of the gap while H_y reverses polarity at the gap centerline. We will assume that H_x is positive for a positive record current, and that H_y is positive on the left-hand side of the gap and negative on the right-hand side. It may be seen then that if tape is moved from left to right with a positive current flowing, the magnetization will be the vector sum of $+m_x$ and $-m_y$. When the tape is moved in the reverse direction the recorded magnetization will be the vector sum of $+m_x$ and $+m_y$.

For this experiment, erased tape was first passed over the record head in the reverse direction, while a positive direct current of a value sufficient to saturate the tape was applied to the head. Thus, the magnetization on the tape was $+m_x$ and $+m_y$. Then the tape was passed over the head in the forward direction. If one now suddenly turns on the same positive current as used before, H_x will still be positive and will not affect m_x. However, H_y will be negative and will produce a step change in m_y from the prerecorded $+m_y$ to $-m_y$. Hence, we will have recorded a step change in m_y, while m_x remains at the positive saturation value. Similarly, if one applies a negative record current, one will record a step change in m_x, while m_y remains at the positive saturation value. The oscilloscope photograph, Fig. 5(a), shows the resulting horizontal and vertical pulses superimposed with identical scale factors. The maximum height of the vertical pulse is approximately 5 per cent of the horizontal pulse height. Note also the shape of the two pulses as compared to the shape of H_x and H_y in Fig. 4. The pulses were also integrated electrically to obtain relative amplitudes of ϕ_x and ϕ_y. The maximum value of ϕ_y was approximately 11 per cent of the maximum ϕ_x. It would be rather interesting to extend this technique to nonsaturation recording and to bias recording and measure relative values of e_x, e_y, ϕ_x, and ϕ_y under various conditions. From the relative values of e_x and e_y in Fig. 5, one can see the e_y is so small that it will contribute negligibly to the shape of the total voltage pulse, at least for saturation and near-saturation recording on ordinary tape. This is in contradiction to Hoagland, who attributes the pulse shape entirely to the sum of the horizontal and vertical reproduce functions, and neglects the effects of the record process. A check on the validity of neglecting e_y is shown in Fig. 5(b) and 5(c), which compares normally recorded pulses with pure horizontal pulses produced with approximately the same record field. The pulses are very nearly identical, and both exhibit a relatively sharp rise and more gradual decay. This same shape could be produced by e_y, but e_y would have to be a much larger percentage of e_x than measured to produce the amount of asymmetry observed. Hence, one may simplify the analysis of the reproduce function by neglecting the vertical component without introducing any appreciable error.



(a)

(b)

(c)

Fig. 5—Recorded pulses. (a) Horizontal and vertical pulses. (b) Normally recorded pulse. (c) Pure horizontal pulse.

Gap Width and Medium Thickness

One now has a tool to evaluate the response of any reproduce head for which $H_x = F(x, y)$ is known. The effects of head-to-tape spacing (y_1) and tape thickness ($y_2 - y_1$) may be included in the evaluation. Unfortunately, the expression for H_x of a standard gap-type head is rather complicated and would be extremely difficult to handle analytically. It was decided, therefore, to obtain values of

$$e_x = K \int_{y_1}^{y_2} H_x dy$$

experimentally for values of y from $y=0$ to $y=$gap width, and to use an approximate expression for values of y larger than the gap width.

To determine

$$K \int_{y_1}^{y_2} H_x dy$$

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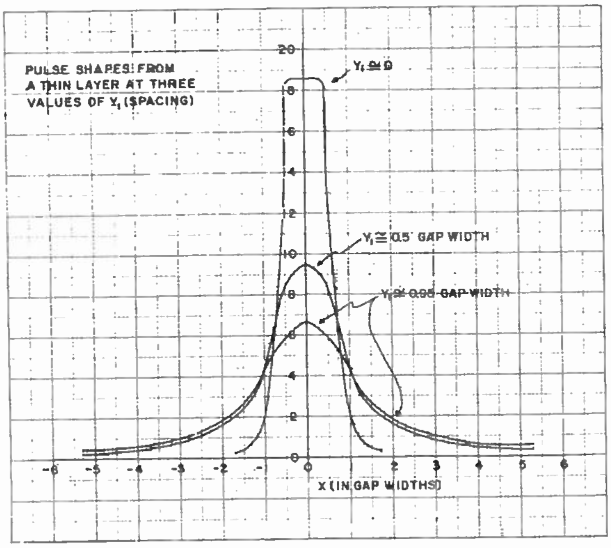

Fig. 6—Pulse shapes from a thin layer at three values of Y_1.

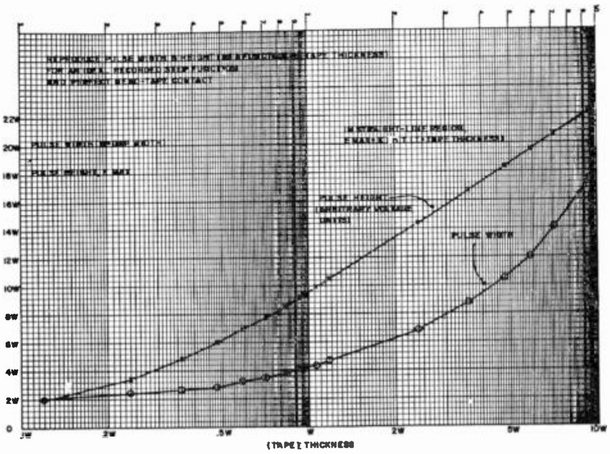

Fig. 7—Reproduce pulse width and height for an ideal step function.

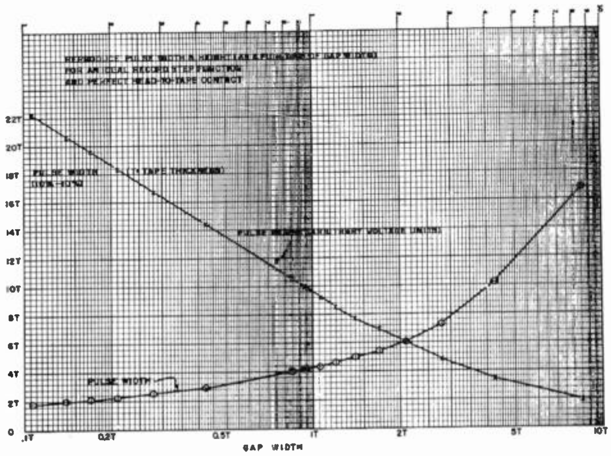

Fig. 8—Reproduce pulse width and height for an ideal step function.

experimentally, a reproduce head with a gap width approximately ten times the oxide thickness was used. Pulses were recorded with a small-gap record head, and it was assumed that the recorded pulse length was negligible compared to the gap width of the reproduce head. The tape passing over the reproduce head was spaced away from the head in consecutive increments equal to the oxide thickness, out to a distance equal to the gap width. Point-by-point measurements of the resulting pulses were made and tabulated. Fig. 6 shows the pulse shapes for $y_1 \cong 0$, $y_1 \cong 0.5$ and $y_1 \cong 0.95$ (gap width). We now have empirical values of

$$K \int_{y_1}^{y_2} H_x dy$$

in steps of 0.1 gap width. To obtain the integral for any region between $y_1 = 0$ and $y_2 = 1.0$ gap width, one may simply sum the experimentally determined values over the desired region.

For values of y greater than the gap width, the effect of gap dimensions is negligible, and the equation for H_x of a head with an infinitely small gap is a very close approximation to the actual field. For an infinitely small gap,

$$H_x = K \frac{y}{x^2 + y^2}$$

$$e_x = K \int_{y_1}^{y_2} \frac{y dy}{x^2 + y^2} = K \ln \left[\frac{x^2 + y_2^2}{x^2 + y_1^2} \right].$$

To extend the experimental data, the value of K may be determined from the pulse voltage at $y_2 = 1$ (gap width), and the integral may be evaluated by setting y_1 equal to the gap width and y_2 equal to values larger than y_1. These values of e_x may be added to the experimentally determined voltages to provide total pulse height and width for any values of y_1 and y_2. In Fig. 7, pulse width (between 10 per cent amplitude points) and pulse height are plotted for the case of a constant gap width of $2a$ and variable tape thickness. The same data are replotted in Fig. 8 for a constant tape thickness and variable gap width. Figs. 7 and 8 indicate that in the range of gap widths and tape thicknesses presently in use, only slight increases in resolution can be obtained by decreasing either gap width or oxide thickness alone. However, if both are decreased by some percentage, the pulse width will decrease by the same percentage.

Effect of Finite Recorded Width

For the above calculations a perfect recorded step function is assumed. In practice, the "step" change will have a finite length along the medium which will produce an increase in the actual reproduced pulse width over the calculated values when y_1 is small. When y_1 is large, the effect of the finite recorded length will be negligible. Since the actual pulse width for very small spacings will be larger than calculated and for large spacings will be the same as calculated, the increase in width with spacing will be somewhat less than shown in Fig. 9.

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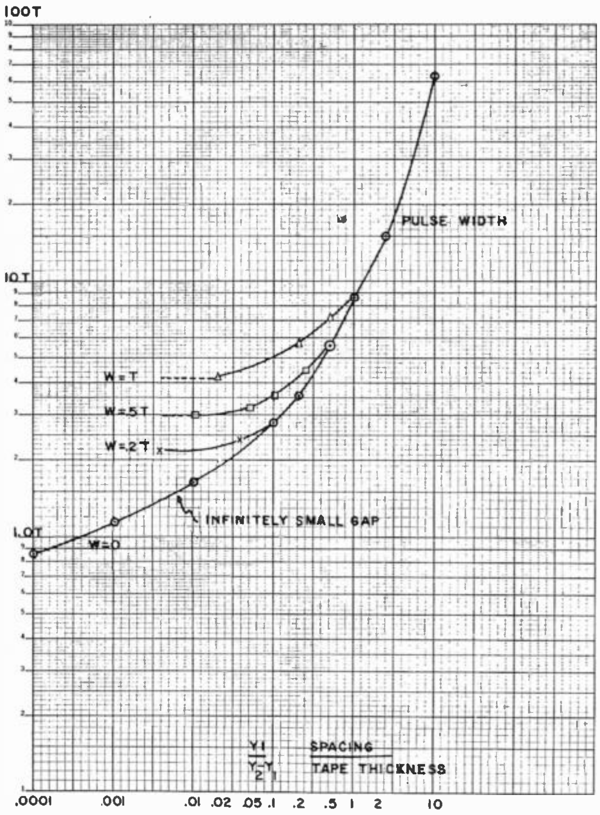

Fig. 9—Pulse width vs spacing.

The expression for reproduce pulse voltage when the recorded step function has a finite length x_1 is derived in the Appendix, and is

$$\frac{e_x}{v} = -\frac{2m_x}{x_1}\int_{y_1}^{y_2}\int_{\bar{x}}^{\bar{x}+x_1} H_x dx dy = \frac{1}{x_1}\int_{\bar{x}}^{\bar{x}+x_1}\left(\frac{e_x}{v}\right)dx$$

$$x_1 = 0.$$

This means that $(e_x/v)x_1=0$ is simply averaged over a distance of x_1 at all values of $\bar{x}$. The effect is that of looking at the pulse through an aperture of width x_1. The width of the pulse should therefore be increased by approximately x_1. To check this, we may compute the effect of x_1 on the output of a head with negligible gap width. For this head

$$\left[\frac{e_x}{v}\right]_{x_1=0} = K \ln\left[\frac{\bar{x}^2 + y_2^2}{\bar{x}^2 + y_1^2}\right]$$

and

$$\frac{1}{x_1}\int_{\bar{x}}^{\bar{x}+x_1}\left[\frac{e_x}{v}\right]_{x_1=0} d\bar{x} = \frac{K}{x_1}\int_{\bar{x}}^{\bar{x}+x_1}\left[\frac{\bar{x}^2 + y_2^2}{\bar{x}^2 + y_1^2}\right]d\bar{x}$$

$$= (\bar{x} + x_1)\ln\frac{(\bar{x}+x_1)^2 + y_2^2}{(\bar{x}+x_1)^2 + y_1^2} - \bar{x}\ln\frac{\bar{x}^2 + y_2^2}{\bar{x}^2 + y_1^2}$$

$$+ 2y_2\left[\tan^{-1}\frac{\bar{x}+x_1}{y_2} - \tan^{-1}\frac{\bar{x}}{y_2}\right]$$

$$- 2y_1\left[\tan^{-1}\frac{\bar{x}+x_1}{y_1} - \tan^{-1}\frac{\bar{x}}{y_1}\right].$$

This expression was evaluated for the case

$$\frac{y_1}{y_2 - y_1}\left[\frac{\text{spacing}}{\text{thickness}}\right] = 0.1$$

for $x_1 = 50$ per cent and $x_1 = 10$ per cent of the pulse width calculated for $x_1 = 0$. When $x_1 = 10$ per cent, pulse width increases 10.7 per cent and pulse height decreases 9.6 per cent. When $x_1 = 50$ per cent of the original width, pulse width increases 61 per cent and height decreases 48 per cent.

The exact effect of x_1 on the output of finite gap heads could be computed by plotting the output pulse for $x_1 = 0$ and graphically averaging over various values of x_1. This has not been done. For any practical reproduce head, it will be sufficiently accurate to use the approximation that pulse width at any x_1:

$$w_{(x_1)} = w_{(x_1=0)} + x_1$$

and

$$\text{pulse height } e_{\max\,(x_1)} = \frac{w_{(x_1=0)}}{w_{(x_1=0)+x_1}} e_{\max\,(x_1=0)}.$$

In most actual recording systems, x_1 will be found to be several times less than $w_{(x_1=0)}$ and the above approximation will be quite accurate.

To compute the effects of head-to-tape spacing, one may evaluate

$$e_x = K\int_{y_1}^{y_2} H_x dy,$$

keeping the oxide thickness $(y_2 - y_1)$ constant and varying y_1. For values of y_1 greater than the gap width, the infinitely small gap formula may be used and an expression derived giving pulse width as a function of tape thickness and the ratio $y_2/y_1 = a$. Pulse height is

$$e_{\max\,(x=0)} = K \ln\frac{y_2^2}{y_1^2} = K \ln a^2 = 2K \ln a.$$

For

$$e = 0.1e_{\max},$$

$$e = K \ln\frac{x^2 + y_2^2}{x^2 + y_1^2} = K \ln a^{0.2}\ \frac{x^2 + y_2^2}{x^2 + y_1^2} = a^{0.2},$$

and

$$y_2 = ay_1, \text{ so } \frac{x^2 + a^2y_1^2}{x^2 + y_1^2} = a^{0.2}.$$

Solving for x,

$$x = y_1\sqrt{\frac{a^2 - a^{0.2}}{a^{0.2} - 1}}.$$

Pulse width $w = 2x$ and tape thickness $T = y_2 - y_1 = y_1(a-1)$ so pulse width/tape thickness =

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$$\frac{2x}{T} = \frac{2\sqrt{\dfrac{a^2 - a^{0.2}}{a^{0.2} - 1}}}{a - 1}. \tag{7}$$

Eq. 7 was evaluated as a function of spacing/tape thickness and the results plotted in Fig. 9. The spacing effect for finite gap heads was computed by numerically adding the measured values of

$$e = \int_{y_1}^{y_2} H_x dy$$

(for $y_1 < W$) to calculated values of

$$e = K \int_{y_1}^{y_2} H_x dy = 2.81 \ln \frac{x^2 + y_2^2}{x^2 + y_1^2}$$

(for $y_1 > W$). For each case $e_{\max}$ was computed first, and the value of x for $e = 0.1 e_{\max}$ was determined by cut-and-try computation. Spacing effect on pulse width was computed in this manner for three ratios of gap-width to tape-thickness, $W = T$, $W = 0.5T$ and $W = 0.2T$, and is plotted in Fig. 9. Pulse height ($e_{\max}$) for the three gap widths and for negligible gap width are plotted in Fig. 10. Note that when spacing is greater than the gap width, the infinitely small gap formula applies. This formula may therefore be used to compute reproduce resolution for many non-contact devices such as magnetic drums.

From Fig. 9 and from experimental data one may estimate the effective head-to-tape spacing present when the oxide is seemingly in contact with the head. When pulses are recorded with a 0.5 mil gap head on 0.5 mil oxide and played back on a 0.25 mil reproduce head, the 10 per cent to 10 per cent width is about 2.5 mils, or five times the oxide thickness. If one subtracts from this a recorded width of one oxide thickness, one has a width of about $4T$. From the $W = 0.5T$ curve of Fig. 9, a width of $4T$ indicates a spacing of $0.16T$ or 0.08 mil. Considering the data accuracies involved, this figure should be accurate within about ±25 per cent, giving an effective spacing of between 0.06 and 0.10 mil. With a spacing of 0.08 mil, and an oxide thickness of 0.5 mil, the pulse width from an infinitely-small-gap head would be $3.3T$ or 1.65 mils, plus the recorded width.

Coil Location

At first glance, it might appear that the location of the pickup coil on a high-permeability ring-type head would have little effect upon the output waveform. This assumption is true only when the pulse repetition rate is high, so that the distance between pulses is considerably less than the total width of the reproduce head. For low repetition rates or single recorded step functions, the situation is somewhat different. When the distance between recorded magnetization reversals is small, and when no reversal is in the region of the gap, most of the flux from the medium will enter one pole piece, follow a path around the rear of the ring, and exit at the other pole piece [see Fig. 11(a)]. For this case, the flux at all points around the rear portion of the head is the same and coil location will have no effect on the output.

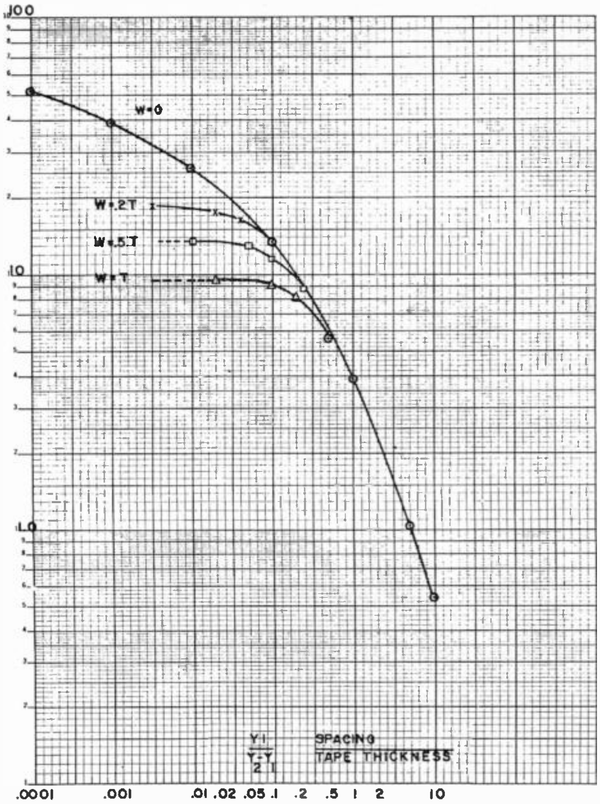
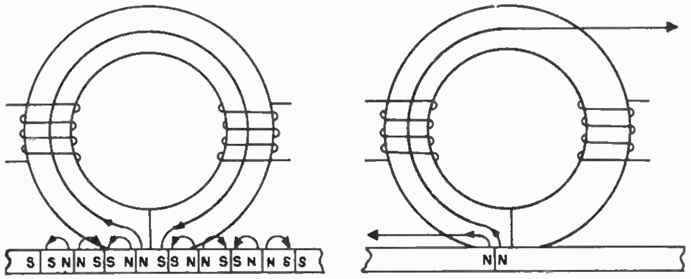


Fig. 10—Pulse height vs spacing.

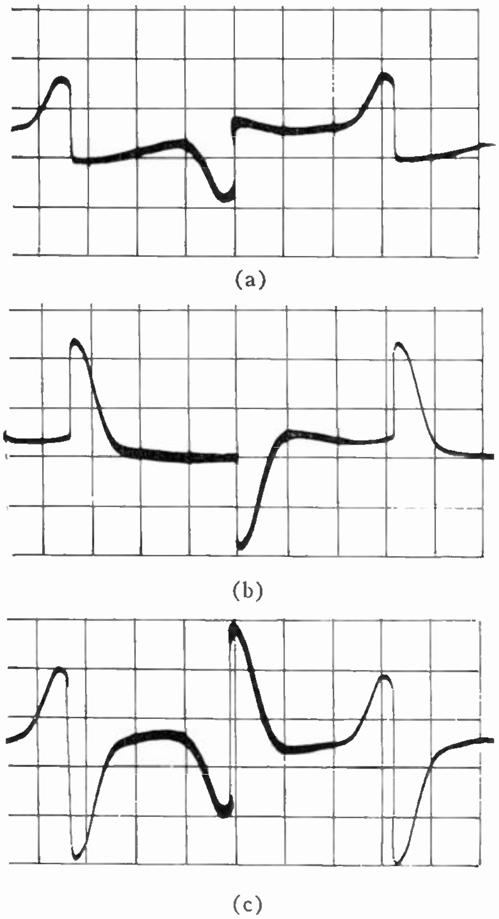


(a) (b)

Fig. 11—Flux paths through reproduce head. (a) Short wavelengths. (b) Long wavelengths.

Now consider a single step function. When it is remote from the head, no flux will pass through the head. When the step is under one pole, flux will enter that pole piece and circulate only through a portion of the head [see Fig. 11(b)]. In this case, coil location becomes important.

To investigate this effect, the voltages from the two coils of a reproduce head were observed both separately and with the coils in series as normally connected. First, the head output was electrically integrated to determine the flux through the coils. Fig. 12 shows the flux waveforms from the two coils and their sum. The flux through the leading coil rises slowly as the recorded step comes into proximity with the pole, then drops suddenly to zero as the step crosses the gap. In the trailing coil, the sequence is reversed. It is the rapid change in flux


(a)

(b)

(c)

Fig. 12—Flux waveforms in reproduce head. (a) Leading coil. (b) Trailing coil. (c) Leading and trailing coils in series.

as the step crosses the gap region which produces the voltage pulse usually observed. The more gradual change of flux away from the gap region produces a very broad, low-amplitude pulse of the opposite polarity, some distance away from the main pulse (see Fig. 13). The areas under these two pulses must be equal because they represent equal changes in flux.

To determine whether there is any time displacement between the pulses from the leading and trailing coils, a reference pulse was recorded on an adjacent track. There was no measurable time displacement between the pulses from the two coils. The pulse shapes appeared to be identical also.

The Recording Medium

General

The most widely used recording medium consists of plastic tape—either polyester or acetate—approximately 1.0 to 1.5 mils thick, and coated on one side with a 0.4 to 0.5 mil layer of iron oxide (Fe_2O_3). Other materials and dimensions have been used, but those mentioned are most common. It is the magnetic characteristics of the oxide which are of primary interest.

Present oxides have a coercive force (H_c) of 230 to 270 oersteds and a retentivity (B_r) of 900 to 1400 gauss. Fig. 14 shows a typical B-H loop for typical tape. The maximum static permeability, B/H, is about 3 or 4, and the incremental permeability, $\Delta B/\Delta H$ may be 10 or 20. The reversible permeability $\Delta B/\Delta H$ in the magnetized state is about 1.8 to 2.0. It is usually assumed that the permeability of the oxide is sufficiently small so that it produces a negligible effect on the shape of the fringing field or a record or reproduce head. Wallace,[4] Westmijze,[2] Gilbert,[1] Von Behren[5] and others all assume a medium permeability of unity for field calculations. Greiner[6] states that the permeability of ordinary recording tapes may be assumed to be approximately 10, and computes the field distribution for this value. Westmijze states that the measured reversible permeability is 3.6, and varies no more than 2 per cent over the range of magnetization from zero to saturation. He

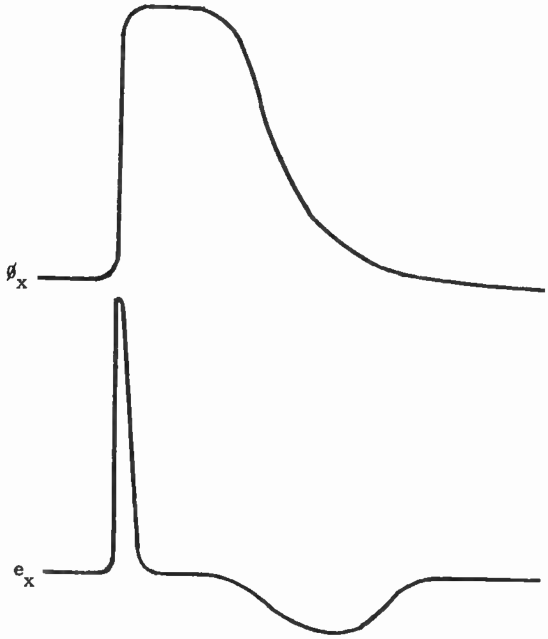


Fig. 13—Flux and voltage waveforms in trailing coil.

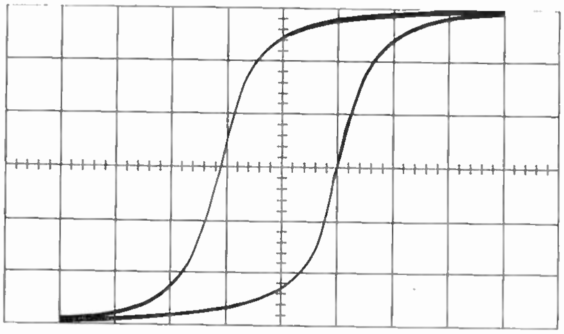


Fig. 14—Typical tape B-H loop.

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[4] R. L. Wallace, Jr., "The reproduction of magnetically recorded signals," *Bell Sys. Tech. J.*; October, 1951.

[5] R. A. Von Behren, "Some design criteria for magnetic tape," *J. Audio Engrg. Soc.*, vol. 3, p. 210; October, 1955.

[6] J. Greiner, "The field distribution of recording heads in the presence and absence of tape," *Nachrichtentechnik;* July, 1955.

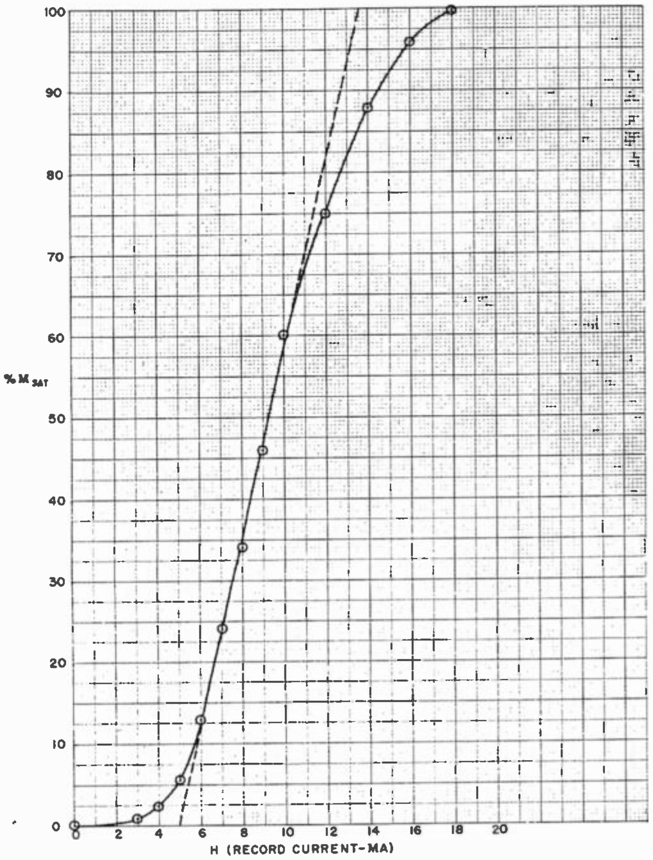

Fig. 15—Oxide magnetization characteristics.

also states that some error is introduced by the assumption of unity permeability, but makes no estimate of its magnitude. Begun[7] simply states that the permeability is approximately 3, and shows a field plot based on this value. For the calculations in this report, a permeability of unity was assumed. It would be rather interesting to ascertain the actual effective permeability of the tape and its effect upon the record and reproduce processes.

Magnetization Characteristics

The initial magnetization characteristics of a typical tape are shown in Figs. 15 and 16. In Fig. 15, per cent remanent induction is plotted vs applied field on a linear scale. On a linear basis, this curve is often approximated as having a zero offset, then rising linearly to saturation. Actually, the curve appears to be fairly linear from approximately 13 per cent to 60 per cent M_{rs}. In Fig. 16, the same curve is plotted on a logarithmic scale. Here it may be seen that M_r is proportional to the fourth power of H for values of M_r up to approximately 30 per cent of saturation.

With NRZ recording the remanent induction after the tape has been subjected to two fields of opposite polarity is of particular importance. Curve B of Fig. 16 shows M_r vs H when each value of H has been applied, first in one polarity and then in the opposite polarity. The effect of the previous magnetization is greatest for small values of M but is significant over the entire range of M. This and the following data were obtained by recording first with a direct current of the desired value and then with a unidirectional square wave of the opposite polarity. The output from the playback head was integrated to measure the flux change. This method does not provide data of the high accuracy which might be possible with more refined techniques, but it should be sufficient for our purposes. In Fig. 17, a group of curves is plotted showing the magnetization characteristics resulting from various levels of opposite polarity premagnetization. From Figs. 16 and 17 it may be observed that to predict the magnetization effect of any field value less than that required for saturation, one must know the previous history or at least the present state of magnetization of the medium.

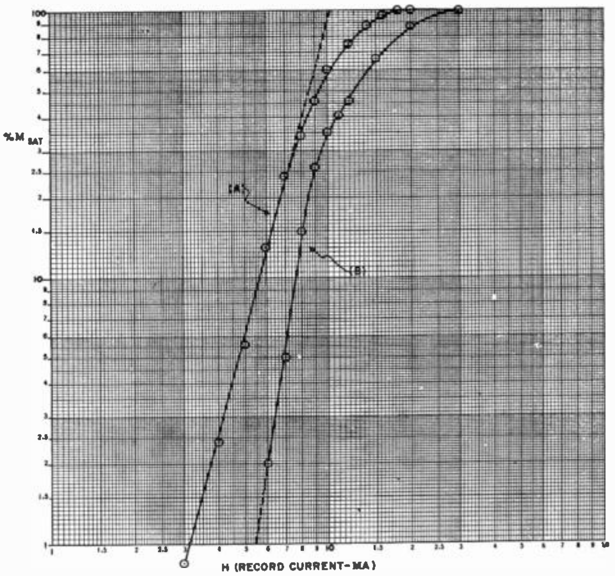

Fig. 16—Oxide magnetization characteristics.

There is one aspect of magnetization which is of significance in magnetic recording about which very little is known. This is the effect of vector rotation of the magnetization field upon amplitude and direction of the remanent induction. Knowledge of this effect would be an aid in analyzing the function of the record head, but must for the present be neglected.

The Record Process

Basic Process

The basic mechanism of the record process must first be established. Then various parameters can be changed and their effect upon the recorded pulse determined. Only the longitudinal components of field and magnetization will be considered. To illustrate the record process, assume that the medium has been moving relative to a record head through which a direct current is flowing. This current is then reversed instantaneously so that no motion need be considered. We may compute

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[7] S. J. Begun, "Magnetic field distribution of a ring recording head," *Audio Engrg.*; December, 1948.

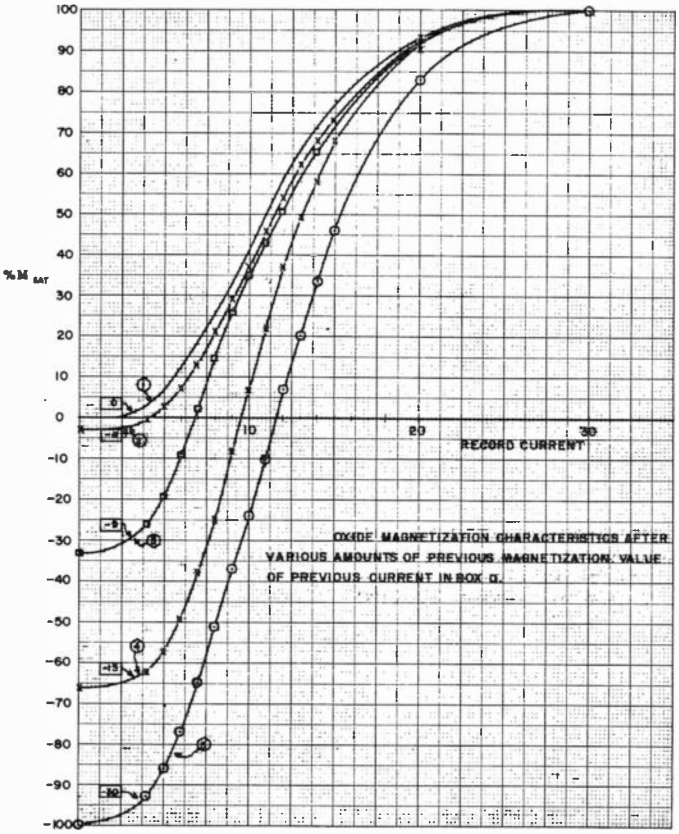

Fig. 17—Oxide magnetization characteristics.

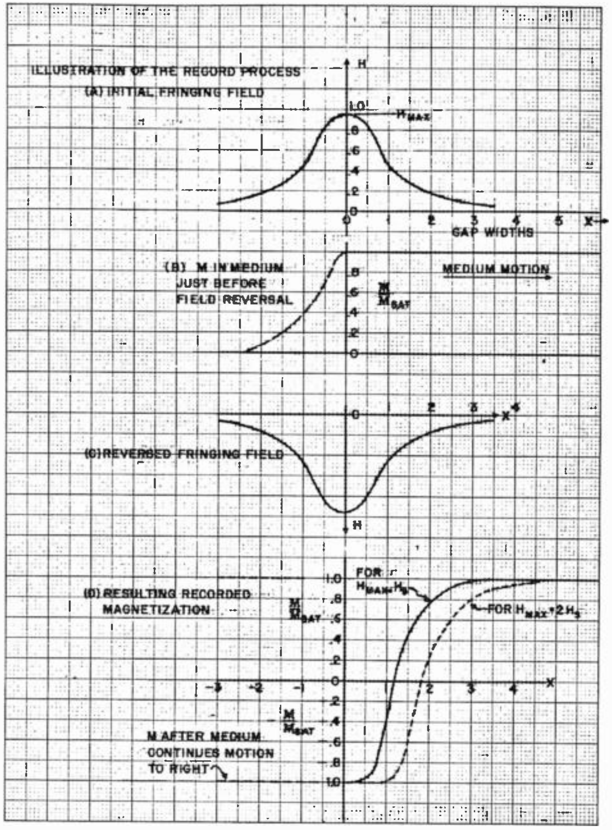

Fig. 18—Illustration of record process.

the magnetization M, which exists in the medium just prior to the current reversal, then compute the effect of the reversed field upon M.

Fig. 18(a) is a plot of the longitudinal field present in the thin layer of oxide located between 0.2 and 0.25 mil away from a 0.5-mil record head. The M which exists before reversal may be computed from curve 1 of Fig. 17. Assume $H_{\max}$ to be just sufficient to saturate the oxide (30 ma in Fig. 16). The resulting M is shown in Fig. 18(b). Now the field is reversed [see Fig. 18(c)]. As all the oxide to the right of the gap center line was previously saturated, M in this region may be computed from the curve 5 of Fig. 17. Fig. 18(d) shows the resulting M. As $H_{\max}$ is sufficient to completely reverse M, the entire transition between $+M_{\max}$ and $-M_{\max}$ will occur to the right of the gap centerline. This will not be true for smaller values of $H_{\max}$. The approximate center of the recorded pulse ($M=0$) occurs at 0.32 mil aft of the gap centerline, and the width between 10 and 90 per cent is 0.7 mil. When the medium moves away from the head, all portions which are now to the left of the gap centerline will be magnetized to $-M_{\max}$.

Effect of Record Current (Field Strength)

The effect upon the recorded pulse of different record currents may also be computed. First, consider a current which produces a field of $H_{\max}=2H_s$. As before, the pulse will be recorded in a region to the right of the point where the head field equals H_s. As this point is farther from the gap centerline than in the previous case, the entire pulse will be displaced farther away from the centerline. The magnetization may be computed in the same manner as before and the resulting pulse is shown as a dashed line in Fig. 18(d).

From Fig. 17 we may observe that when $H_{\max}$ is equal to or larger than H_s, the location at which M crosses zero will always occur at the point where $H=0.4\ H_s$. Likewise, the 10 per cent point will occur where $H=0.6\ H_s$ and the 90 per cent point will occur where $H=0.2\ H_s$. It is interesting to note that shorter pulses can be recorded on an oxide in which a smaller percentage change in H produces the change in M from 10 to 90 per cent.

When $H_{\max}=0.5\ H_s$, the pulse will be recorded closer to the gap center line. For this case, $H_{\max}$ is insufficient to completely reverse the magnetization even at the gap center line. Hence, the transition from $+M_{\max}$ to $-M_{\max}$ will be not completed until the oxide moves far enough to the right so that the previous magnetization is small enough to have a negligible effect upon M. This sequence is shown in Fig. 19. Not only has the location changed, but the shape is different from that of the first two pulses. The distance from $M=0$ to $M=-M_{\max}$ is considerably greater than for $M=+M_{\max}$ to $M=0$. The derivative of this (moving from right to left) will rise rapidly to a peak and then drop more slowly to zero. Such a shape is characteristic of pulses recorded below saturation (see Figs. 4 and 5).

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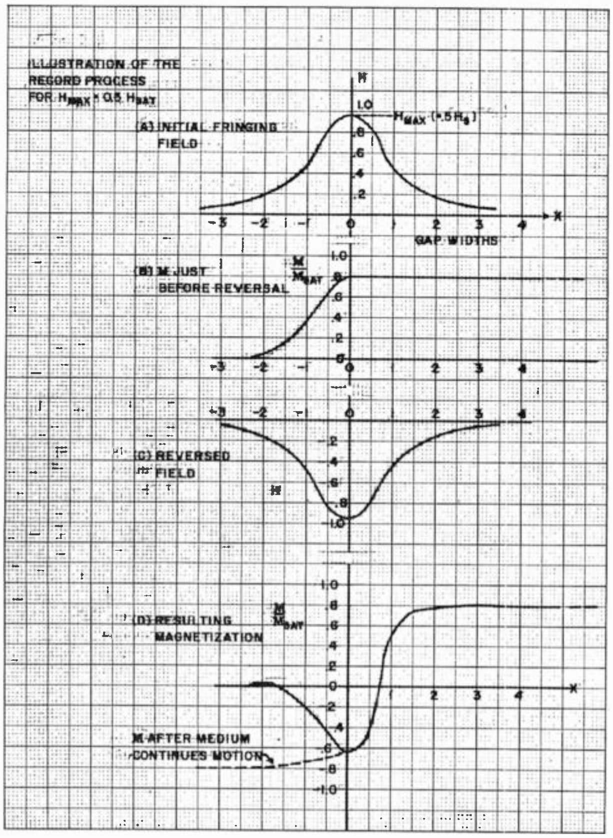
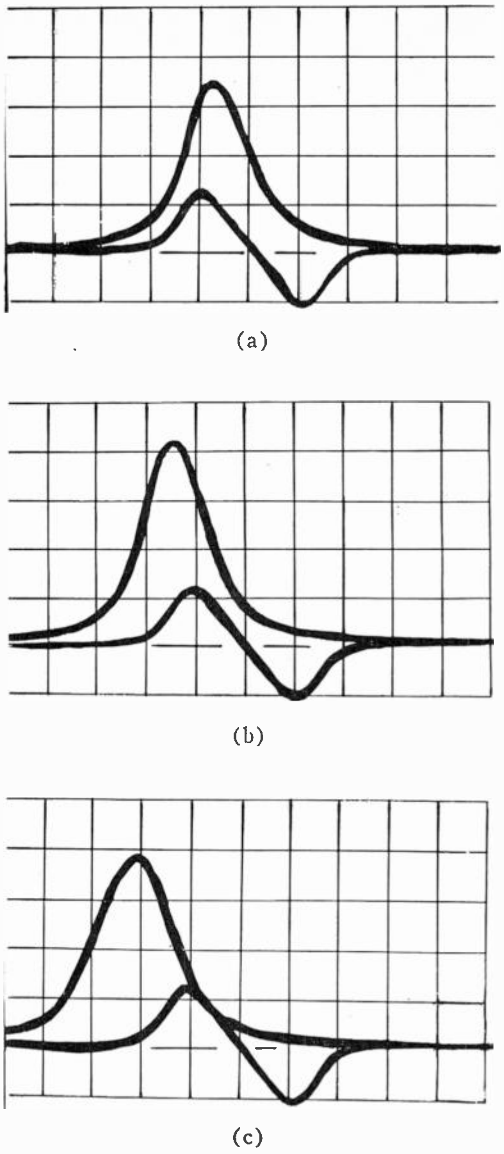


Fig. 19—Illustration of record process.

It has been shown theoretically that the record current will affect both the shape and the location of the recorded pulse in a given layer of the oxide. To verify this experimentally, a ten-times scale model was used. A record head with a 5.0 mil gap was constructed and normal tape with approximately 0.5-mil oxide was spaced 2 mils out from the head. A reference unit pulse was recorded on an adjacent track. The zero crossing of this pulse during reproduction was used to establish the location of the record head gap centerline. A 0.25-mil reproduce head was used, with no spacing between oxide and head. Photographs of the pulses resulting from three different record currents are shown in Fig. 20.

To show the effect of record current amplitude on pulse location in a practical system, NRZ pulses were recorded with a 0.5 mil head and reproduced on a 0.25 mil head using instrumentation-grade tape. As before, a reference track was used to locate the record gap centerline. The distance from the record gap centerline to the pulse peak was measured for various record currents. These data are plotted in Fig. 21. The total change in pulse location as the current was varied from 7 to 50 ma was 0.55 mil, slightly more than one record gap width. It would be quite interesting, though outside the scope of this investigation, to determine the effect of this variation in point of recording upon direct-recorded analog signals. If present to the same degree as measured here it could produce considerable distortion at short wavelengths.


(a)

(b)

(c)

Fig. 20—Effect of record current on pulse location and shape. (a) Record current = 120 ma. (b) Record current = 240 ma. (c) Record current = 480 ma.

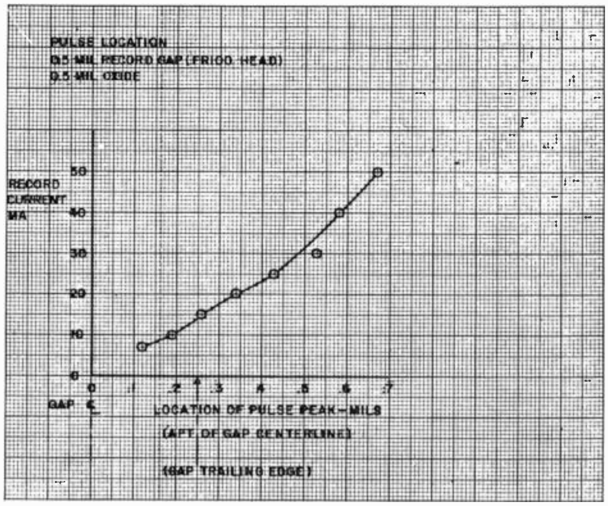


Fig. 21—Pulse location vs record current.

Oxide Thickness

Next, consider the effect of distance from the head upon the recorded pulse. Since the shape and intensity of the fringing field vary with distance, so will the width and location of the recorded pulse. As may be seen in Fig. 6, there is a significant variation in field shape within the oxide thickness, which must therefore be taken into account in analyzing the record process.

To illustrate this depth effect, the field in layers at 0.1 to 0.15 mil and 0.5 to 0.55 mil away from a 0.425-mil gap head is shown in Fig. 22. The H scale is arbitrary. If a value of H_s is chosen such that saturation will occur in both layers, the location of the recorded pulse may be determined by finding the points at which each field is 0.2 H_s, 0.4 H_s and 0.6 H_s. These field levels are shown on Fig. 22 for $H_s = 0.5$.

By projecting the intersections of each H level with the field-strength curves onto the x axis, the width and location of the pulses recorded at the two depths within the oxide can be determined.

To obtain actual data on the width and location of the pulses in each layer of the oxide, a large-gap record head was used. The tape was spaced varying distances away from the head during recording and was reproduced in contact with a 0.25-mil head. A unit pulse on an adjacent track was used for reference. In this manner, a profile of the magnetization throughout the oxide thickness was obtained, which is shown in Fig. 23. From these data, the effect of gap width and oxide thickness upon recorded pulse width can be computed.

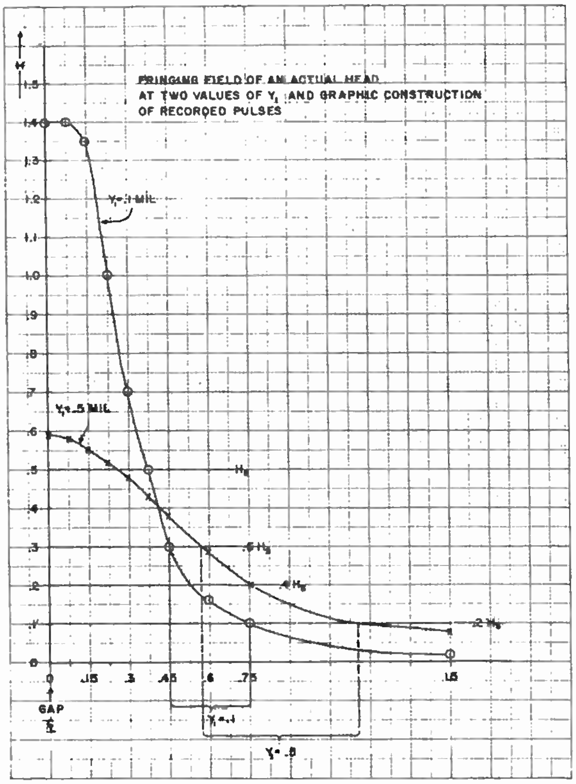


Fig. 22—Graphic construction of recorded pulses.

Since both the width and location of the pulse vary with depth, some arbitrary means must be chosen to obtain a single value for the pulse width in a given thickness of tape. The means used here was simply to take the average of all the widths throughout each particular thickness.

This should provide a fairly accurate width to add to the reproduce pulse width, because the reproduce head also averages over the thickness of the tape. In Fig. 24, average pulse width-oxide thickness is plotted vs gap width/oxide thickness for two values of record current. The curves were extrapolated to zero gap width by assuming that since the recorded width will be zero at the head surface, the average width will be one-half the width of the pulse in the outermost oxide layer. The width in the outermost layer was assumed to be the same as for a finite gap head where y is equal to or larger than the gap width.

From Fig. 24 it can be seen that only a slight increase in over-all pulse resolution may be achieved by using very small record gaps. Comparing Fig. 24 with Fig. 8 it can be seen that within the range of gap widths and tape thickness presently in use, the average recorded pulse width is approximately one-fifth the width of an ideal reproduce pulse from the same head.

Spacing

In analyzing the effects of spacing the medium away from the reproduce head, only the shape of the fringing

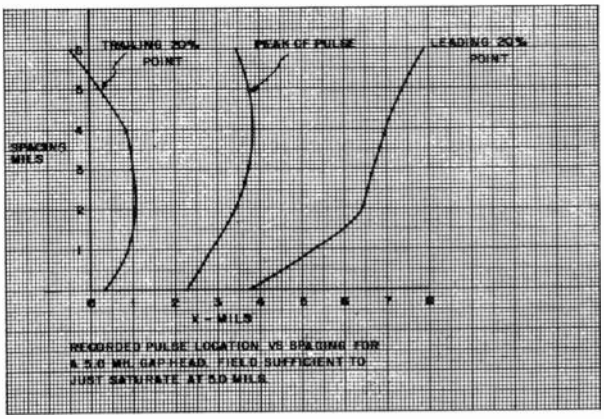


Fig. 23—Recorded pulse location vs spacing.

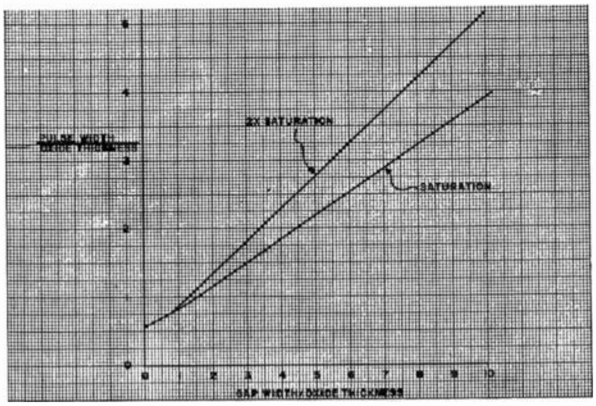


Fig. 24—Recorded pulse width vs gap width.

field at any location had to be determined. For the record function, however, the actual field strength relative to saturation field strength must also be considered. For this reason, two different conditions of spacing will be analyzed separately: first, the condition where field strength is constant and the medium is displaced temporarily away from the head, as during a dropout caused by foreign matter on the surface of the medium; second, the condition where the medium is intentionally spaced away from the head and the record current is adjusted for this spacing. To illustrate both cases analytically, assume that the average recorded pulse width throughout the medium is equal to the recorded width in a small layer at the center of the medium thickness, and that the fringing field is that produced by an infinitesimal gap. Both assumptions are quite accurate for values of y equal to or greater than the gap width.

For the first condition, the effect on the pulse may be observed graphically as the medium is displaced in a region in which at maximum displacement $H_{\max}=H_s$. The fringing fields at various values of y for an infinitesimal gap are plotted in Fig. 25. According to the stated condition, $H_s=0.2$. Then H_1, H_2, and H_3 are the field strengths at which 10 per cent, 50 per cent, and 90 per cent of $\Delta M_{\max}$ will occur. Values of pulse width and x_0 (at 50 per cent $\Delta M_{\max}$) obtained from Fig. 25 are plotted in Fig. 26. Notice that x_0 increases less than each increment of y. As the medium is spaced farther away, $H_{\max}$ is no longer sufficient to saturate the medium. Analysis is considerably more difficult in this region, so only the approximate location x_0 for a limiting condition will be determined. Experimental data will provide a more complete picture. At some value of y, $H_{\max}$ will not be sufficient to reverse the M initially recorded at the gap centerline ($x=0$), but will be sufficient to bring M to zero. This occurs at approximately $H_{\max}=0.1\ H_s$ ($y\cong 50a$). Hence, at this value of y, x_0 will be zero. Therefore, x_0 which was increasing in the region where $H_{\max} \gtrless H_s$, must decrease in the region where $H_{\max}<H_s$.

To confirm the above results experimentally, a tape with approximately a 0.5-mil oxide was spaced away from a 0.5-mil gap record head while the record current was held constant at two different values. The resulting pulse widths and x_0's are plotted in Fig. 27. The widths and locations of the pulses vary in the same manner as in Fig. 26. Because of record current limitations, the fields (and therefore the x_0's) in Fig. 27 are not as large as those assumed for Fig. 26.

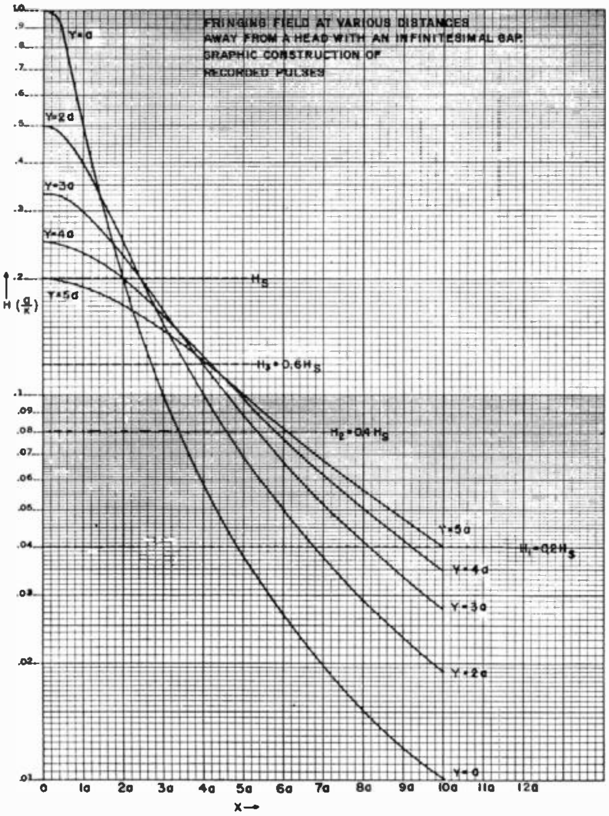


Fig. 25—Graphic construction of recorded pulses.

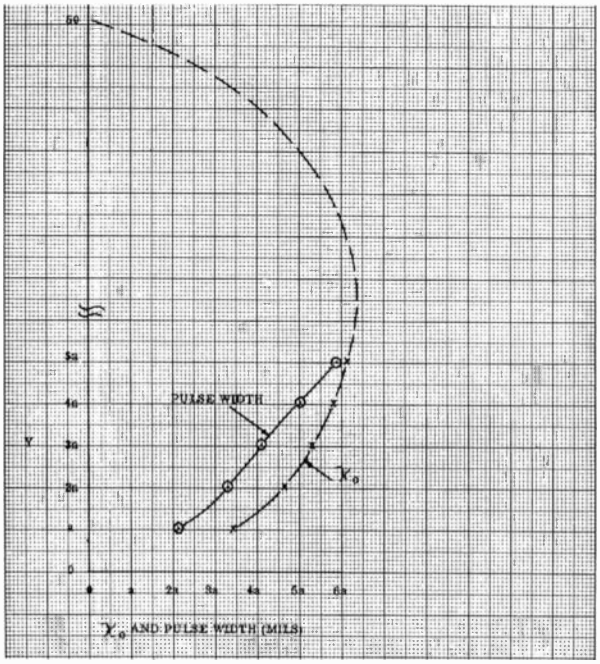


Fig. 26—Pulse width and location vs spacing (theoretical).

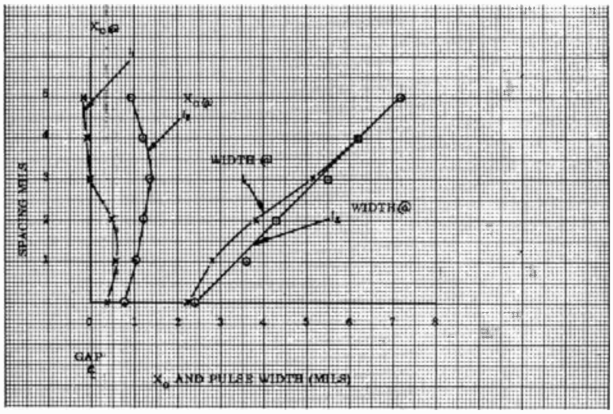


Fig. 27—Pulse width and location vs spacing (experimental).

The second spacing condition is simpler to analyze. We shall assume that at each value of y the record current is adjusted so that $H_{\max} = H_s$. We may then derive an expression for pulse width and x_0 from the fringing field equation. If

$$H = K \frac{y}{x^2 + y^2}$$

then

$$H_{\max(x=0)} = \frac{K}{Y}, \qquad \frac{H}{H_{\max}} = \frac{y^2}{x^2 + y^2}.$$

Solving for the x at which H occurs, we get

$$x_{(H)} = y\sqrt{\frac{H_{\max}}{H} - 1}.$$

We have assumed that for each case $H_{\max} = H_s$, so

$$x_{(H)} = y\sqrt{\frac{H_s}{H} - 1}.$$

The pulse width will be the difference between $x_{(10 \text{ per cent})}$ and $x_{(90 \text{ per cent})}$ which occurs at $H = 0.2H_s$ and $H = 0.6H_s$, respectively. Hence

$$\text{P.W.} = y\left[\sqrt{\frac{H_s}{0.2H_s} - 1} - \sqrt{\frac{H_s}{0.6H_s} - 1}\right] = 1.2y,$$

and x_0 will occur at

$$H = 0.4H_s, \text{ or } x_0 = y\sqrt{\frac{H_s}{0.4H_s} - 1} = 1.2y.$$

We may similarly compute the 10 per cent to 10 per cent reproduce width for an ideal recorded pulse.

$$\text{P.W.} = 2x_{(H=0.1H_s)} = 2y\sqrt{\frac{H_s}{0.1H_s} - 1} = 6y.$$

The ratio is $6/1.2 = 5$, which is the same ratio determined earlier by experimental means. To find the approximate over-all width after recording and reproduction on a thin layer of oxide spaced at y from the head, we may simply add the record and reproduce widths, giving P.W. $= 7.2y$.

EFFECT OF PREVIOUS HISTORY

In digital recording, information is often recorded on a medium which has been previously recorded and not erased. Under certain conditions this recording can produce an undesirable error in pulse location, which will occur when the recording current is such that $H_{\max}$ is insufficient to reverse completely the previous magnetization. This effect is illustrated graphically in Fig. 28. The pulse location depends upon the polarity of the previous magnetization. To determine the amount of location error, long-wavelength NRZ pulses were recorded first, then shorter-wavelength pulses were recorded on the same section of tape at the same record current. During reproduction the oscilloscope was synch'ed on negative pulses and the displacement between following positive pulses was measured.

In Fig. 29, the displacement, as a per cent of reproduced pulse width, is plotted vs per cent of saturation record current. Saturation current in this case is the current required to magnetize initially the oxide to its maximum remanence. A record current of twice saturation was required to make the displacement unmeasurable.

CONCLUSION

Expressions have been derived and experimental data obtained from which a reasonably accurate prediction may be made of the record and reproduce performance of a magnetic pulse recording system. A technique has been developed for measuring the vector direction of magnetization of the recording medium. It has been shown that the resolving power of a head is five times poorer for reproducing than for recording, which suggests the direction in which future head developments might take. For instance, a nonreciprocal reproduce-only head may be very desirable.

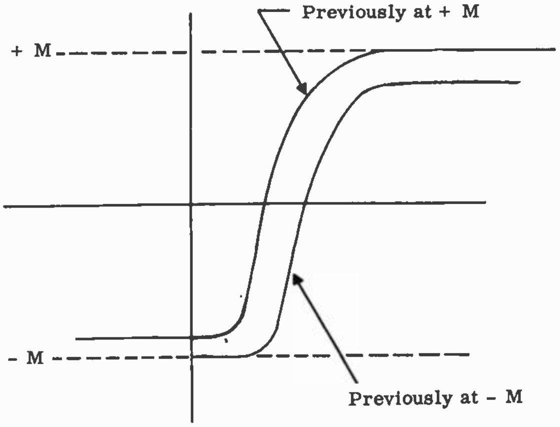


Fig. 28—Effect of previous magnetization.

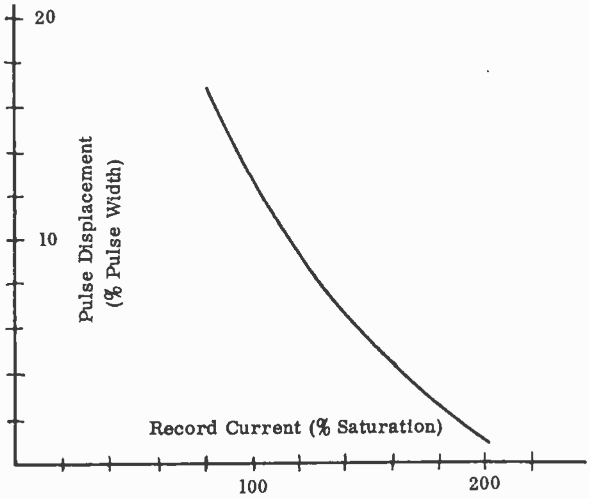


Fig. 29—Pulse displacement resulting from previous magnetization.

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It is suggested that some of the analysis methods described could be utilized to provide a better understanding of the record and reproduce functions in direct bias recording.

APPENDIX I

DERIVATION OF REPRODUCE HEAD OUTPUT FOR A RECORDED STEP FUNCTION OF FINITE WIDTH

Assume a "step" function with a finite constant slope, as in Fig. 30. For the region between $\bar{x}$ and

$$\bar{x} + x_1, \quad M_x = -m_x + 2m_x\left(\frac{x - \bar{x}}{x_1}\right).$$

The flux through the reproduce head is

$$\phi = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} M_xH_xdx = \int_{y_1}^{y_2}\int_{-\infty}^{\infty} M_xH_xdxdy$$

where y_1 and y_2 are the limits of the magnetic medium. Consider the integral with respect to X: it may be expressed as the sum of integrals over various regions between

$$-\infty \text{ and } +\infty. \quad \int_{-\infty}^{\infty} M_xH_xdx = (-m_x)\int_{-(\bar{x}+x_1)}^{-(\bar{x})} H_xdx$$
$$+ (-m_x)\int_{-\infty}^{-\bar{x}(+x_1)} H_xdx + (-m_x)\int_{-(x)}^{0} H_xdx$$
$$+ (-m_x)\int_{0}^{(\bar{x})} H_xdx + \int_{(\bar{x})}^{(\bar{x}+x_1)}\bigg[-m_x$$
$$+ 2m_x\left(\frac{x - \bar{x}}{x_1}\right)\bigg] H_xdx + m_x\int_{(\bar{x}+x_1)}^{\infty} H_xdx.$$

Because of symmetry of H_x,

$$-m_x\int_{-\infty}^{-(\bar{x}+x_1)} H_xdx + m_x\int_{(x+x_1)}^{\infty} H_xdx = 0$$

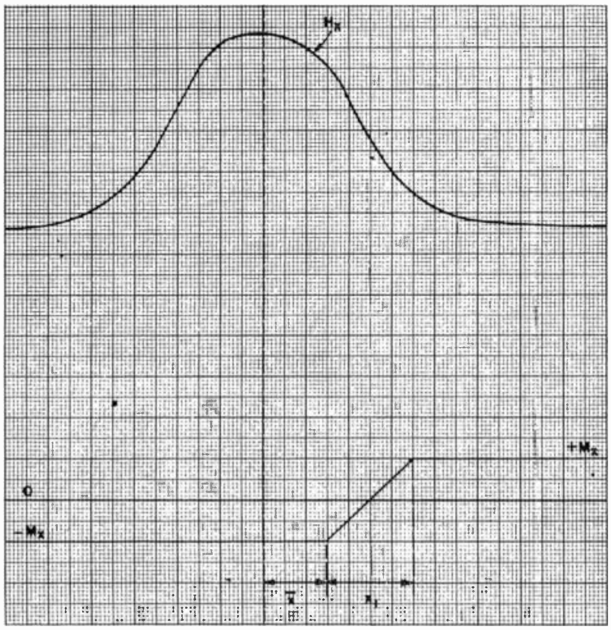

Fig. 30—Recorded step function of finite width.

and

$$(-m_x)\int_{-(\bar{x})}^{0} H_xdx + (-m_x)\int_{0}^{\bar{x}} H_xdx = -2m_x\int_{0}^{\bar{x}} H_xdx.$$

$$\therefore \int_{-\infty}^{\infty} M_xH_xdx$$
$$= (-m_x)\int_{-(\bar{x}+x_1)}^{-(\bar{x})} H_xdx - 2m_x\int_{0}^{\bar{x}} H_xdx$$
$$+ \int_{\bar{x}}^{(\bar{x}+x_1)}\left[-m_x + 2m_x\left(\frac{x - \bar{x}}{x_1}\right)\right] H_xdx$$
$$= (-m_x)\int_{-(\bar{x}+x_1)}^{-(\bar{x})} H_xdx - 2m_x\int_{0}^{\bar{x}} H_xdx$$
$$- m_x\int_{\bar{x}}^{(\bar{x}+x_1)} H_xdx + 2m_x\int_{\bar{x}}^{(\bar{x}+x_1)} \frac{x - \bar{x}}{x_1} H_xdx.$$

Again because of symmetry,

$$-m_x\int_{-\bar{x}x+x_1)}^{-(\bar{x})} H_xdx - m_x\int_{\bar{x}}^{(\bar{x}+x_1)} H_xdx$$
$$= -2m_x\int_{\bar{x}}^{(\bar{x}+x_1)} H_xdx.$$

Then

$$-2m_x\int_{0}^{\bar{x}} H_xdx - 2m_x\int_{\bar{x}}^{(\bar{x}+x_1)} H_xdx = -2m_x\int_{0}^{(\bar{x}+x_1)} H_xdx.$$

$$\therefore \int_{-\infty}^{\infty} M_xH_xdx$$
$$= -2m_x\int_{0}^{(\bar{x}+x_1)} H_xdx + 2m_x\int_{\bar{x}}^{(\bar{x}+x_1)}\left(\frac{x - \bar{x}}{x_1}\right) H_xdx.$$

Now $e_x/v = d\phi_x/d\bar{x}$, so the above integrals must be differentiated with respect to $\bar{x}$. The derivative may be found from

$$\frac{d}{d\bar{x}}\int_{u}^{v} f(x, \bar{x})dx = \int_{u}^{v}\frac{\partial}{\partial\bar{x}} f(x, \bar{x})dx + \frac{\partial v}{\partial\bar{x}} f(v, \bar{x}) - \frac{\partial u}{\partial\bar{x}} f(u, x).$$

$$\therefore \frac{d}{d\bar{x}}\int_{-\infty}^{\infty} M_xH_xdx$$
$$= -2m_xH_{x(\bar{x}+x_1)} - \frac{2m_x}{x_1}\int_{\bar{x}}^{(\bar{x}+x_1)} H_xdx + 2m_xH_{x(\bar{x}+x_1)}$$
$$= \frac{-2m_x}{x_1}\int_{x_1}^{(x_2+\bar{x})} H_xdx$$

and

$$\frac{e_x}{v} = \frac{-2m_x}{x_1}\int_{y_1}^{y_2}\int_{\bar{x}}^{(\bar{x}+x_1)} H_xdxdy$$
$$= \frac{1}{x_1}\int_{\bar{x}}^{(\bar{x}+x_1)}\left(\frac{e_x}{v}\right)_{(x_1=0)} dx.$$

This is simply the $[e_x/v]$ for a zero-length step function averaged over a length of x_1.

High-Density Magnetic Recording*

JAMES J. BROPHY†

Summary—**By improving the mechanical properties of magnetic recording heads and recording media, it has been possible to demonstrate consistent recordings at information densities up to 40,000 cycles per inch. No fundamental magnetic limit to the maximum recording density has been detected. The major mechanical limitation appears to be the effective head-tape separation due to mechanical surface roughness of the medium. Tape noise arises from both body and surface effects, but their relative importance is not clear. High-frequency recording in the region of several megacycles introduces no special problems with heads of suitable design, such as the outside coil head. Based on present experimental results, a maximum recording density of the order of 100,000 cycles per inch is predicted.**

INTRODUCTION

THE major improvement in magnetic recording, required to increase its usefulness and application, is the increase of recorded information density on the magnetic record. A substantial increase will lead both to improved high-frequency recording and to slower tape speeds for audio recording. The high-frequency recording application involves problems of two different types: the recording of ultra-short wavelengths on the record, and the high-frequency difficulties of losses and stray fields. For slow tape speeds at audio frequencies, the short wavelength problem is dominant. Thus, for both applications, the short wavelength problems of suitable heads, satisfactory tape (both mechanical and magnetic properties), and tape noise are important.

This paper is concerned with a study of the possibility of substantially increasing the information density in magnetic recording. The purpose is to indicate more fully the basic limitations of magnetic recording with emphasis on short wavelength effects, but also with consideration to high-frequency applications. The experiments reported here were undertaken in order to establish whether or not a magnetic limitation to short wavelength recording presently exists.

MICROGAP AND HIGH-FREQUENCY HEADS

General considerations appear to indicate that mechanical properties of the record medium are the major limitations to attainment of higher recording densities. Preliminary experimental work using microgap heads fabricated in our laboratory was undertaken in order to determine if this was indeed the case. These heads were fabricated with a 20-micro-inch mechanical gap which, in principle, should be capable of a resolution approaching 50,000 cycles per inch.

The results obtained indicate that 13,500 cycles per inch can be realized in a wide-band system using tape which has received some surface polishing. Fig. 1 shows typical results. The considerable improvement of aged over fresh tape should be noted. In this work, the tape was aged by repeatedly running it over the recording head in order to smooth the surface. These data may also be taken as a typical example of the present state of development that can be attained easily in the laboratory. It should be noticed that satisfactory audio recordings can be realized with this system with tape speeds as slow as one-tenth of an inch per second.

Since the head used should in principle be capable of approaching densities of 50,000 cycles per inch, these results appear to indicate that the record medium is the major limitation. The fall-off in the response at high densities is attributed to an effective head-tape separation caused by the surface roughness of the tape. Further evidence for this is found in Fig. 1 where the lack of a clearly defined null followed by a secondary response maximum is evident. If the recording densities were head limited, such a null and secondary maximum would be expected.

Although these recording heads appear to be capable of high-density recording, subject to the limitations of the record medium, they are not satisfactory for high-frequency work because of large inductive reactance and internal magnetic losses. In order to get some feeling for these problems, a new head structure, which has been termed an "outside coil head," was investigated in some detail. In the outside coil head structure, the tape rides over a magnetic defining gap having an effective 1-turn short. The pickup coil is located on the opposite side of the tape. Coupling between the pickup coil and the defining gap occurs through fringing fields. This structure

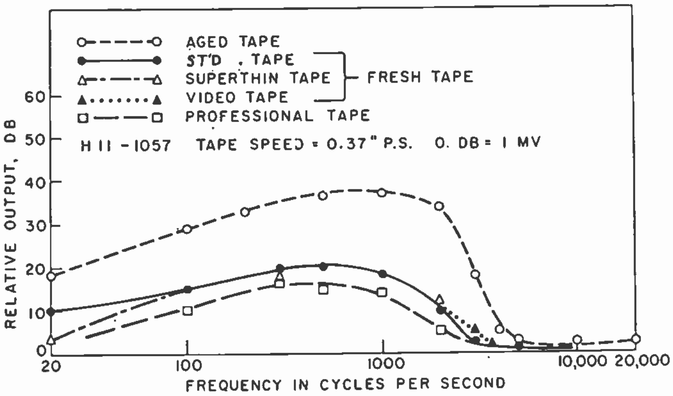

Fig. 1--Frequency response of various magnetic tapes at 0.37 inch per second with a microgap head.

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* Manuscript received by the PGA, September 15, 1959.

† Physics Res. Div., Armour Research Foundation, Chicago, Ill.

has the advantage that the coil may be made very small, which raises its self-resonant frequency, and the defining gap need not be narrow in the dimension perpendicular to the tape surface, so that good wear properties are achieved.

In spite of its rather unfavorable appearing magnetic structure, it proves possible to record and play back with the outside coil head. It is found that recording densities of the order of 20,000 cycles per inch may be achieved with this system. These results appear relatively independent of frequency, so that recordings in the megacycle range are possible. Preliminary studies of the effects of bias in the recording of high frequencies have not been as encouraging. A maximum density of only 4000 cycles per inch at frequencies of the order of 1 mc has been obtained using dc bias and the outside coil head. The loss in recording density caused by bias is not clearly understood.

The results at high recording densities are shown in Fig. 2 together with a theoretical prediction of the response due to a 60-micro inch surface roughness. It seems clear from these results that again the high-density limitation is the effective head-tape contact produced by an irregular record surface. Except for the degradation due to bias, recordings up to several megacycles are obtained at modest tape speeds.

The experimental result that the outside coil head is capable of recording densities in the range 20,000 cycles per inch at both low and high frequencies indicates that high-frequency effects in the outside coil head are small. An analysis of the magnetic configuration of an outside coil head has been carried out and shows that a small frequency dependence must exist at the very highest frequencies. This would be indicated by a decrease in performance at frequencies beyond about 5 mc. The experimental results are apparently not accurate enough in this region to show the effect. It is concluded that this head structure is quite suitable for both high-frequency and high-recording density applications. The major limitation on information density appears to be the mechanical condition of the record medium surface.

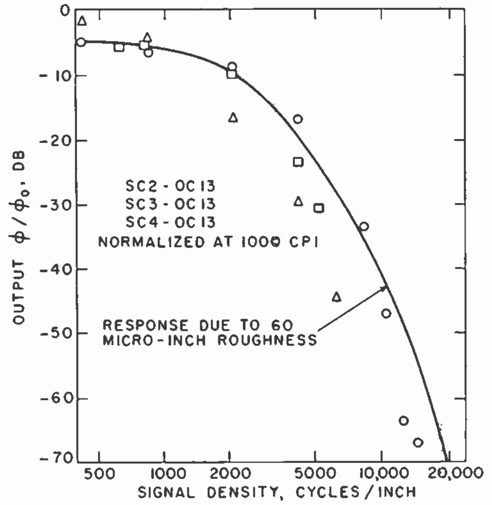


Fig. 2—Comparison of experimental and theoretical response curves of outside coil heads. The theoretical curve assumes a 60-micro-inch tape surface roughness.

A number of other microgap magnetic recording heads were fabricated in order to further confirm this result. A typical head useful for laboratory study and having a well-defined mechanical and magnetic gap is shown in Fig. 3. The fabrication of this head is such as to assure a good gap geometry. This form of head is used in our further experiments on high-density recording discussed below. Several attempts to fabricate microgap heads of standard configuration using ferrite material for the magnetic core have been made. The low-loss properties of ferrites may allow an efficient head of standard shape at high frequencies, the principal problem being the production of a mechanically stable fine gap. Preliminary results on the first of such heads are encouraging, but considerably more work is required.

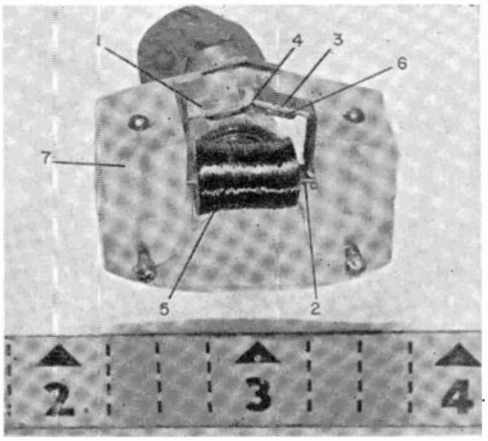
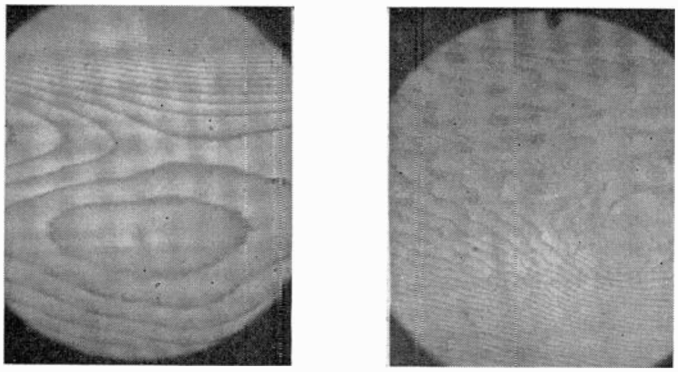


Fig. 3—Armour Research Foundation recording-playback head no. 10.

Recording Surface

The experimental work discussed above indicates that the mechanical condition of the magnetic recording surface appears to be the major limitation to high-density recording. It is a consistent fact that well-aged tapes produced by repeated passage over the recording head result in higher-density recordings. Similar effects may be achieved by the polishing of the tape surface with an abrasive stone.

We have investigated the surface roughness of magnetic recording tape by a technique of optical microinterferometry. Typical microinterferograms of the front and back surface of a smoothed tape are shown in Fig. 4. It is found that such smooth tapes may have a 10-micro-inch deformation over a linear distance of about 1 mm. It is also clear from Fig. 4 that there may be correlation between the irregularities on the front and back of the tape. In addition, the oxide side exhibits considerably greater fine-grain structure because of the presence of the magnetic material.



(a) (b)

Fig. 4—Microinterferograms of the two sides of a polished magnetic recording tape. Each fringe represents a vertical distance of 2500 Å. (a) Mylar. (b) Oxide.

Noise in Magnetic Recording

A second aspect of improving the signal response of magnetic recording is the noise signal generated by the motion of the tape past the head. Under many experimental conditions in the laboratory, this noise source provides the basic limitation to signal detection. The origin of tape noise postulated to be due to the inhomogeneous nature of oxide tapes has been investigated analytically. Available expressions for the noise caused by this mechanism have been extended, and better agreement between predicted and observed tape noise is obtained for demagnetized tapes.

However, a number of studies of tape noise have indicated a minimum in the tape noise power spectrum. The minimum is not predicted by this analysis nor by the extension of it. It is possible that an additional component of noise generated by magnetic surface irregularities exists. This source would be particularly important for the saturated tape condition.

An analysis of the noise due to this mechanism has shown that the noise power is proportional to the square of the frequency rather than to the frequency directly as in the body-noise case. Much of our experimental data show a linear dependence and the absence of a minimum discussed above. Other experimental works, particularly those reporting a minimum, show a higher dependence of noise power on frequency. Thus, there is some evidence that both noise sources may exist and may be important, depending upon the detailed conditions. On the basis of the analysis so far carried out, it should be possible to distinguish experimentally between surface and body effects by the frequency dependence of the noise power.

The apparatus used to investigate tape noise is relatively straightforward. The output of the head is fed to a low-noise high-gain preamplifier followed by a tunable filter and a true rms vacuum tube voltmeter. Typical results obtained for standard tape are shown in Fig. 5. The very considerable increase in noise level when the tape is moving over that with the tape stopped is an indication of how important tape noise may be. Increases of the same order of magnitude are found in comparing demagnetized tape to saturated tape. The results of Fig. 5 show a linear increase of noise power at high frequencies and only a slight suggestion of a minimum. The noise at low frequencies is severely influenced for these measurements by the problem of splices in the tape loop. The passage of the splices over the head produces very large transients which are difficult to overcome. It has not proved convenient to run long lengths of tape because of the difference in the noise properties in the tape over long distances.

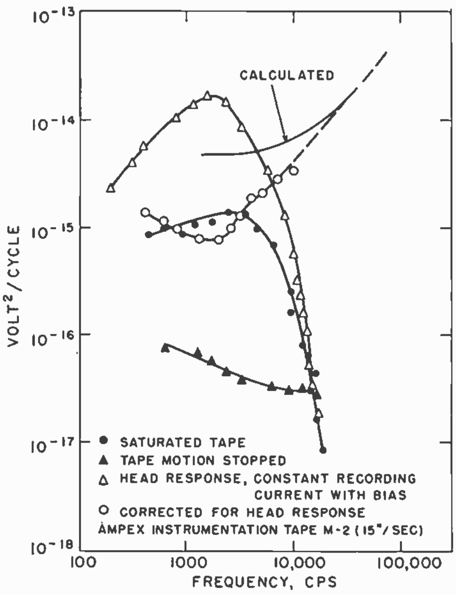


Fig. 5—Experimental measurements of tape noise.

Ignoring the as yet not clearly established effect of surface noise, it is possible to extrapolate present results on maximum recorded density to estimate what the ultimate recorded density may be. Taking present experimental data and assuming a 10-micro-inch recording gap, a head-tape distance of 10 micro-inches, a recording density of 90,000 cycles per inch is predicted. This prediction is based on our present understanding of tape noise and assumes no fundamental magnetic limit to the minimum wavelength.

High-Density Recording

In order to carry out conveniently the experimental work at extremely high recording densities, the disk recorder shown in Fig. 6 has been constructed. The disk configuration was chosen for convenience in producing ultra-smooth magnetic recording surfaces together with stable operation at slow speeds. The major feature of the system is the extensive rim loading of the turntable used to obtain uniform velocities at slow speeds. Very slow speeds are useful in order to enable carrying out the investigations in the audio frequency range, thereby

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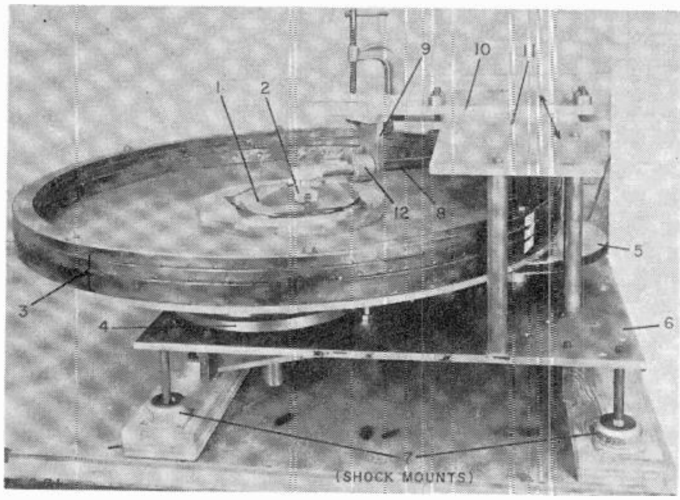

Fig. 6—Magnetic disk recorder.

separating high-frequency effects, as such, from high-density effects. The disk recorder has also been useful in permitting the polishing of the surface of the record medium and in designing an ultra-smooth record surface.

Results obtained to date with this system have shown a recording density of 40,000 cycles per inch. Typical data obtained with the disk recorder are shown in Fig. 7. In spite of the greatly increased recording density shown in the figure, there appears to be still no evidence for a head limited effect or a magnetic limitation. We attribute the limitation still to surface roughness effects producing an effective head-tape separation.

Consideration of the mechanical precision required of a magnetic recording system to utilize fully even those densities obtained in the laboratory shows that the precision required is quite substantial. However, once the existence of a magnetic limit is ascertained, the desirability of attempting this mechanical precision for any particular application may be evaluated more fully.

Conclusion

This research has shown that by improving the mechanical properties of magnetic heads and tapes it is possible to increase recording densities to at least 40,000 cycles per inch with a predicted increase to 90,000 cycles per inch which is dependent upon attaining suitable mechanical precision. No fundamental magnetic limit to the maximum recording density has been observed as yet. The major mechanical limitation appears to be head-tape contact, which is primarily due to the mechanical surface roughness of the record medium.

High-frequency recording into the several-megacycles range appears to offer no major problems in heads of suitable design. The outside coil head seems to be a most attractive configuration for high-frequency work. However, this work has included no studies of high-frequency effects in the tapes themselves. Tape noise appears to arise from both body and surface effects, and while an analytical technique that may distinguish between these processes has been developed, tape noise is not yet well understood.

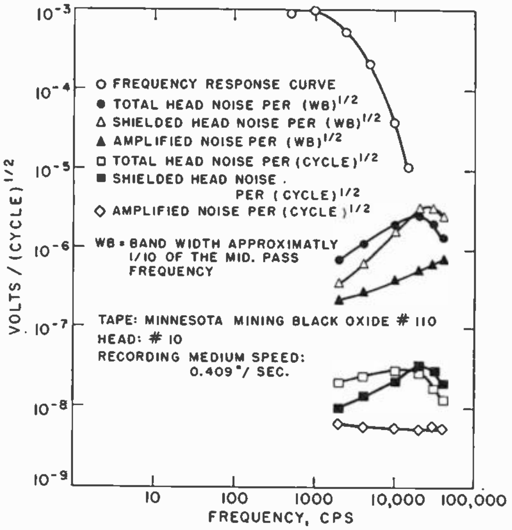

Fig. 7—Output and noise characteristics of disk recorder with microgap head showing a maximum recording density of 40,000 cpi.

Acknowledgment

The author expresses his appreciation to T. T. Kikuchi, M. Camras, and R. D. Sears who made major contributions to this study, and to P. Padva, R. F. Tooper and N. S. Kapany who contributed in certain areas.

World Radio History

A Compatible Tape Cartridge*

MARVIN CAMRAS†

Summary—**Magnetic recording is recognized as a superior medium for stereophonic entertainment, but its popularity has been handicapped by inconvenience of threading and high cost. A new approach is a tape cartridge of very low cost, which is compact, and fully protects the record. The cartridge is completely automatic on a machine designed for its use, and yet will operate manually on present tape recorders.**

IF tapes are to compete with phonograph disks for recorded music, they must be convenient to handle and comparable in price. Cartridge loading provides convenience, but usually raises cost which is already on the high side.

The cartridge described in this paper costs only a few cents. As shown in Fig. 1, it has the appearance of a small molded spool, sealed by a plastic leader. The cartridge is placed into the slot of an automatic machine (see Fig. 2), after which it operates without further handling.

However, an automatic machine is not required. The cartridge fits the shaft of any present recorder, and may be threaded manually. In this case, we may either remove the leader or provide a takeup reel which accepts the leader. Similarly, we can play present-day tape libraries manually, on automatic machines. This two-way compatibility is attractive. The owner of a tape recorder can try the new records before he invests in an automatic machine. The record manufacturer and dealer have only one package to stock, and are insured a ready market even before new recorders are in use.

OPERATION OF THE CARTRIDGE

As may be seen from Fig. 3, the cartridge consists of a spool with a central opening that fits present recorders. A peripheral bead at the inside edge of the flanges allows the one-quarter-inch tape to pass with ample clearance, but holds an end leader in place to form a seal which protects the tape from dust when the cartridge is off the machine. A hook at the end of the leader is designed to latch with the mechanism (see Fig. 4).

Fig. 5 explains the principle of operation. When the cartridge is inserted in the slot, a shaft goes through its hub and drives it counterclockwise until its leader engages a catch on the end of an internally prethreaded machine leader. The prethreaded leader then pulls the cartridge leader on to the takeup spool, thus engaging the tape with the head. The machine operates in a forward direction until reversed, playing either for a second record in the opposite direction or for high speed rewind.

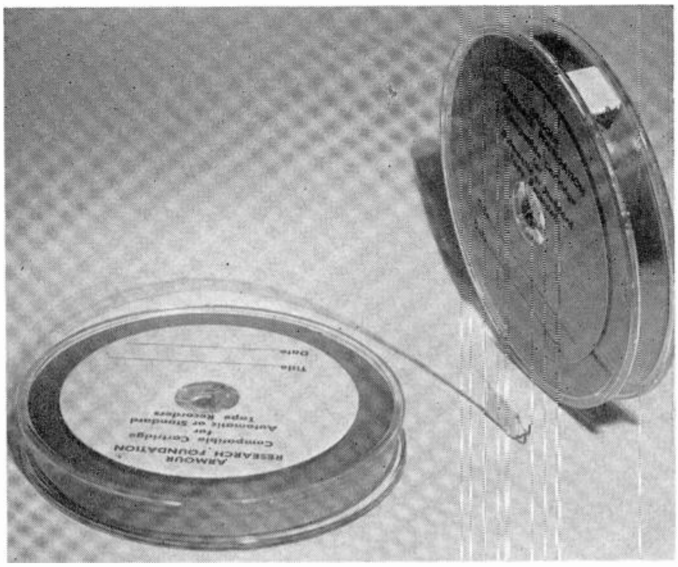

Fig. 1.

Fig. 2.

The automatic machine is shown in Fig. 6, with the cover removed from the magazine receptacle, showing the prethreaded leader in place.

Fig. 7 demonstrates how an adapter is applied to a commercial machine. Here the cartridge is placed on the shaft for loading and turned slightly by hand until the spool leader engages the prethreaded leader on the machine. Thereafter, the recorder is used in its normal manner.

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* Manuscript received by the PGA, October 14, 1959. Presented at the National Electronics Conference, Chicago, Ill., October 12, 1959.

† Armour Research Foundation, Chicago, Ill.

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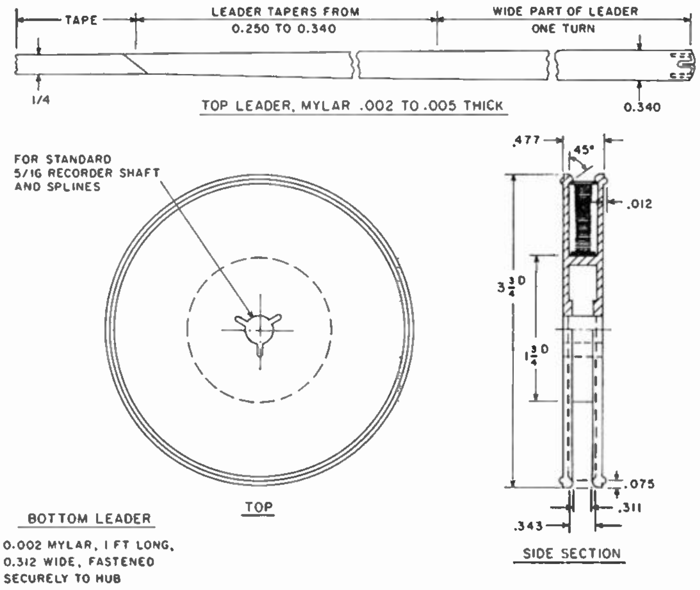

Fig. 3—3.75 OD cartridge.

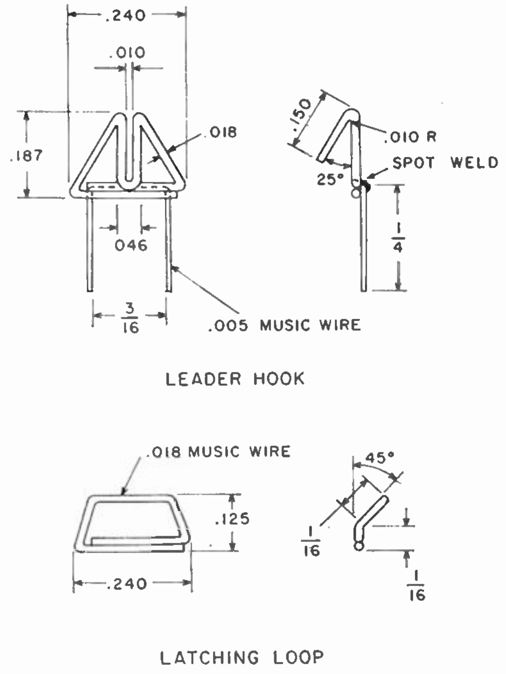

Fig. 4—Hook and loop for cartridge.

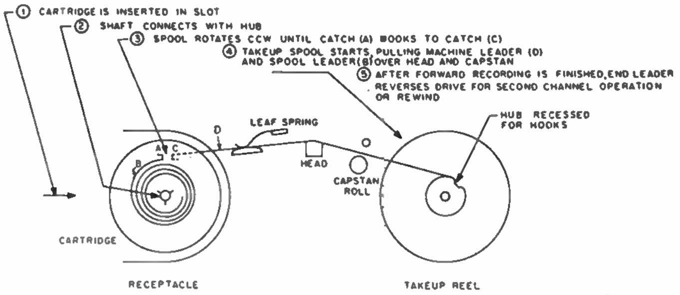

Fig. 5—Operation of tape cartridge on a magazine.

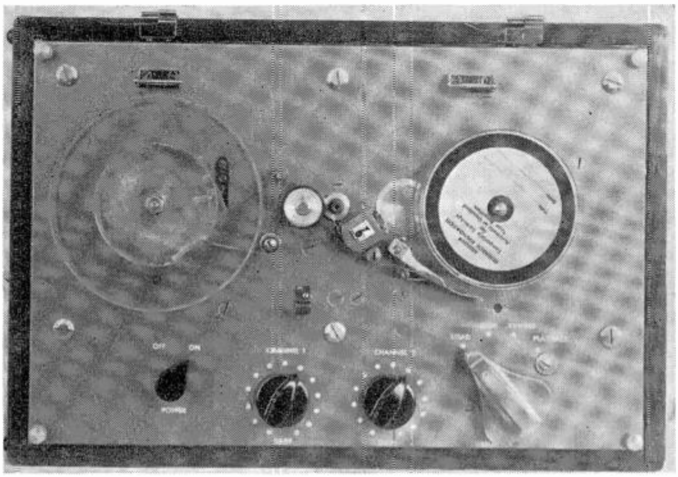

Fig. 6.

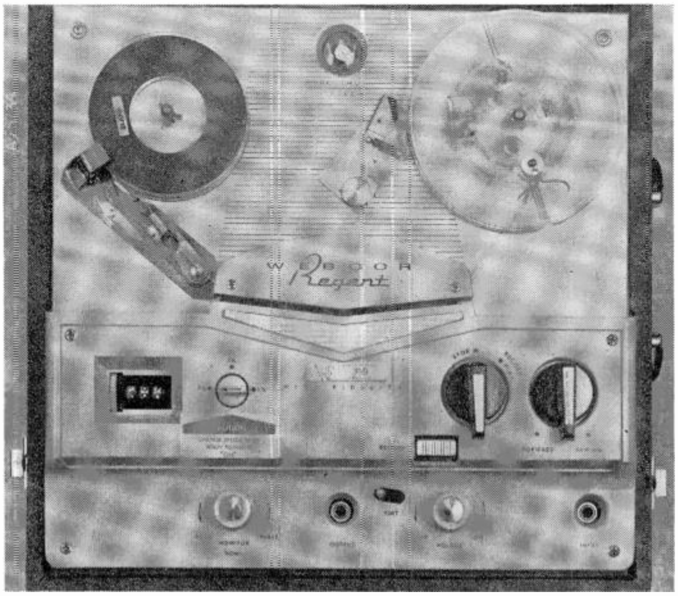

Fig. 7.

Cartridge Sizes

Standardizing on one or two preferred sizes of cartridge is desirable, so that packages can be alike, even though a given recorder can accept a range of sizes.

Tape Thickness

To help choose the most useful sizes, charts were made of playing time (and feet of tape) vs outside diameter of the cartridge. Fig. 8 is a design graph for cartridges using tape which is 1.33 mils thick over all. This tape is almost universally available, both with mylar or cellulose acetate backing, and is designated by names such as 50 per cent extra-play, plus 50, 1-mil backed tape, etc. Fig. 9 is a similar design graph for 1.0-mil thick tape; this type is called double-play, or one-half-mil backed tape. Fig. 10 is for 2.0-mil thick tape.

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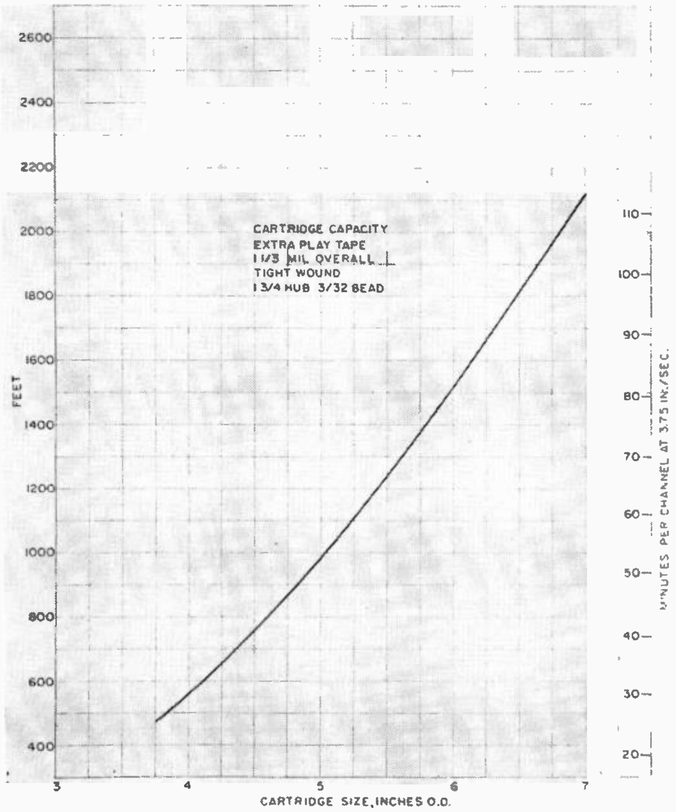

Fig. 8—Design graph for $1\frac{1}{3}$-mil tape.

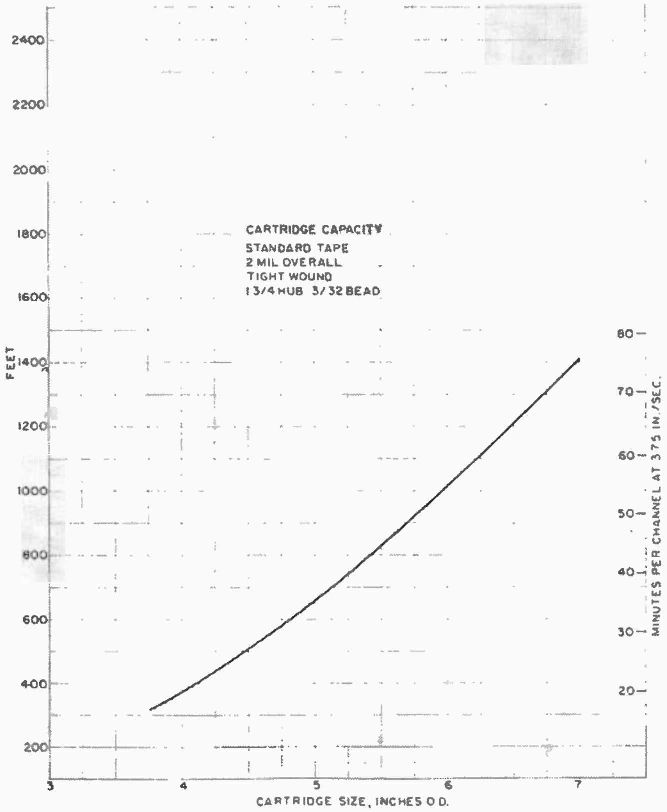

Fig. 10—Design graph for 2-mil tape.

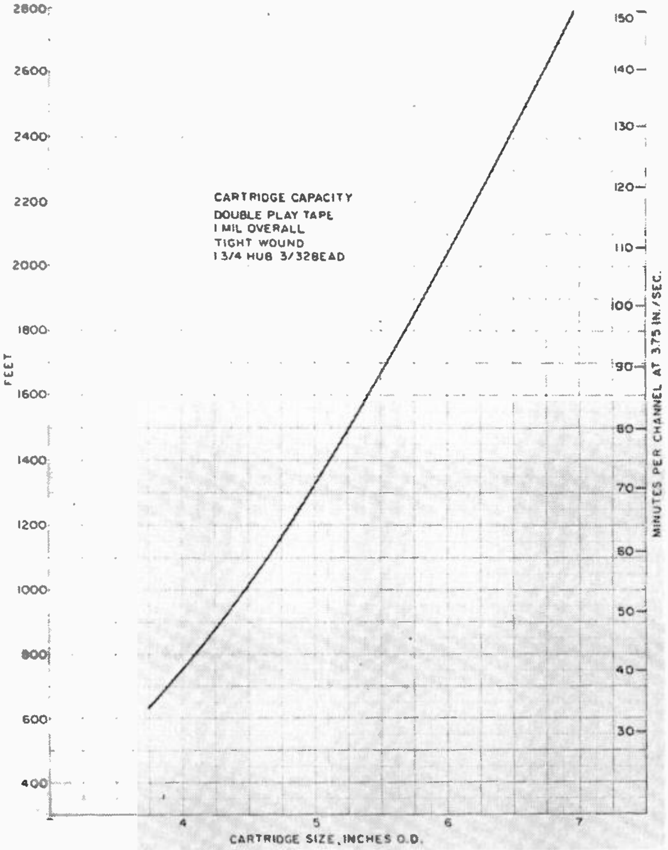

Fig. 9—Design graph for 1-mil tape.

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Of these three sizes, the best compromise seems to be the 1.33-mil tape. It is more compact and less expensive per foot than 2.0-mil tape with the same backing, and is relatively free from breakage, stretching, and mechanical troubles sometimes encountered with the thinner 1.0-mil tape.

Program Time

The next step is to choose maximum continuous playing time for recorded music. While there has been much debate on this point, we can profit from experience in the phonograph industry, where about twenty minutes per side of a long-play disk is customary. Recording directors and arrangers keep this in mind, and since the same performances are often released on tape as well as on disk records, the tape should accommodate somewhat over twenty minutes. We may note that in rare instances a disk may have up to thirty minutes on a side, at a sacrifice in quality. We can match this without deviating from the cartridge size by going to a thinner tape; this seems better than standardizing on a larger cartridge which will rarely be filled.

Fig. 8 shows us that a 3.75-inch OD cartridge plays about 24 minutes per channel at a speed of 3.75 inches per second. For 7.5 inches per second, a 5.0-inch cartridge plays 24 minutes or more.

Fidelity vs Cost

If it is decided that recorded tapes should compete on the basis of quality rather than price, then a 7½-inch per second speed seems most practical at the present state of the art. Although the 3¾-inch per second speed has often been demonstrated as meeting high standards of fidelity, there is no question that in the hands of a nontechnical consumer the 7½ speed will sound better, because it is not as critical with respect to wow and flutter, dirt accumulation at the head, azimuth alignment, etc. We can double the playing time (or halve the cost) by using four tracks on ¼-inch tape instead of two tracks, with very little change in quality. Considering all these factors, we arrive at the following as a reasonable specification for the "highest fidelity" market:

Speed	7½ inches per second.
Tape	1.33-mil (over all) acetate or mylar base, one-quarter-inch wide.
Tracks	4, for two-way stereo.
Playing Time	24 minutes each way (48 total for stereo, or over 1½ hours of monophonic).
Cartridge Size	5-inch OD.

This size has the playing time of a 12-inch stereo disk. The fidelity is about the same as present day stereo tape, which means that it is better than stereo disks for low distortion, low cross talk, and low intermodulation noise. Retail price of a 5-inch reel of unrecorded, name brand, extra-play tape is now $2.34. This may be used as a starting point in estimating the selling price of a recorded 5-inch cartridge.

Most people will be satisfied with sound of somewhat lesser quality, but which still equals or exceeds that of the average high-fidelity installation. Here the 3¾-inch speed is adequate. Tape cost is cut in half, and the small size cartridge is attractive and easy to handle. If other considerations outlined previously are equal, we arrive at the following specifications:

Speed	3¾ inches per second.
Tape	1.33-mil (over all) acetate or mylar base, one-fourth-inch wide.
Tracks	4, for two way stereo.
Playing Time	24 minutes each way (48 total for stereo, or over 1½ hours of monophonic).
Cartridge Size	3¾-inch OD.

Again, this is equivalent in playing time to a 12-inch stereo disk. Retail price of the tape and reel is about half that of the 5-inch size or roughly a dollar. Potentially the fidelity is high, probably superior to reproduction from inner grooves of a stereo disk. Magnetic recording technology has improved steadily, and as quality is upgraded we expect that eventually the 3¾-inch speed will produce sound quality meeting the highest standards.

With this small size of cartridge, a collection of tape records can be carried in a small hinged drawer in front of the recorder, so that any record may be picked up and immediately inserted in the playing slot. A drawer 4×4×10 inches holds 20 records, giving 16 hours of stereo, or 32 hours of monophonic sound. The 3¾ OD cartridge may not be too bad even for the 7½-inch per second customer. At this speed, it holds 24 minutes of stereo and takes care of music which would occupy one side of a disk. It may be desirable to market high-quality music in 24-minute units rather than 48-minute units.

Other Sizes

While most music doesn't require more than 48 minutes, a few selections may run for an hour. These few cases can be handled on the 3¾ reel by using extra thin mylar double-play tape. Alternatively, we may select a 4⅛ spool which carries 60 minutes of extra-play tape (see Table I). This somewhat larger spool can still be standardized for 40 to 48 minutes by using a larger inside hub.

Fig. 3 is a drawing of the recommended 3¾-inch OD "small" cartridge. Table I gives playing time of cartridges under various conditions.

The main need for cartridges as large as 7 inches OD is to allow someone who already has a collection of tapes to change over to a cartridge loading. In addition, a 7-inch size stores many hours worth of recording with slower speeds and multiple tracks.

In Conclusion

Two cartridge sizes, (3¾ OD and 5-inch OD), appear adequate for most uses. These give continuous playing

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TABLE I

Cartridge Size and Thickness of Tape	Total Playing Time—Minutes					
	4 Tracks 3.75 Inches/Second Stereo	4 Tracks 3.75 Inches/Second Monophonic	4 Track 7.5 Inches/Second Stereo	4 Track 7.5 Inches/Second Monophonic	2 Track 7.5 Inches/Second Stereo	2 Track 7.5 Inches/Second Monophonic
3.75 inches OD 1.3 mil over-all (450 feet)	48	96	24	48	12	24
3.75 inches OD 1 mil over-all (600 feet)	64	128	32	64	16	32
(4.12 inches OD) 1.3-mil tape (560 feet)	60	120	30	60	15	30
(4.12 inches OD) 1-mil tape (747 feet)	80	160	40	80	20	40
5 inches OD 1.3-mil tape (900 feet)	96	192	48	96	24	48
5 inches OD 1-mil tape (1200 feet)	128	256	64	128	32	64
7 inches OD 1.3-mil tape (1800 feet)	192	384	96	192	48	96
7 inches OD 1-mil tape (2400 feet)	256	512	128	256	64	128

in multiples of 24 minutes, which fits with all music presently arranged for phonograph records.

The 3¾-inch size ought to be the preferred one, with the 5-inch size an additional standard for longer play or higher speed.

APPLICATIONS

As compared with hand-threading of present day recorders, the advantage of any cartridge is ease in handling the record. Many possible designs of cartridge have been proposed. All of them, including the one described here, have advantages and disadvantages when compared with one another. Some advantages of our design are the following:

1) low cost—possibly competitive with disk records,
2) compatible—operates on present machines, and fits all present and proposed future standards for ¼-inch tapes,
3) protects the record,
4) compact,
5) reliable—can be spliced and repaired as with a spool recorder,
6) adaptable for automatic changer or "juke box" operation.

It is apparent that the cartridge will ordinarily be rewound before it is removed from the machine. This is only a minor disadvantage, since it is done anyway on present recorders 99 per cent of the time. Ideally a two-way drive should be used with a record that plays in both directions; the tape will then be in the cartridge after playing in the back direction, and no separate rewinding step is necessary. Because they are so convenient, we envision two-way machines as common and as simple as present day two-speed machines. Economy recorders may, of course use rewinding and/or flopover features just as we do now.

Immediate Use of Cartridges

At the present time, the cartridge is an attractive package for marketing tape, both blank and recorded. Its closed sides and protective leader are well worth a few cents increased price, even if we disregard automatic machines which may come in the future. The cartridges may be used conveniently on an ordinary machine by removing the hook and by using a takeup reel designed to take the leader.

In buying tape in such a package, the customer is assured that he will be able to utilize automatic machines when they are released. Also, when a large number of records of this type are already in the hands of customers, a machine manufacturer has a ready market for his new models.

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Design Alternatives

From the systems described in this paper, it is noted that at least three alternatives are possible:

1) a completely automatic machine,
2) a semi-automatic machine modified from present production,
3) use of the cartridge and leader (hook omitted) on present machines.

Other possibilities which suggest themselves may be mentioned. A music system for the automobile requires only one-hand (drop-in-the-slot) operation. An automatic changer for cartridges is possible. A "juke box" can be made to use these records. Music stores may sell a recording service instead of recorded tapes. They need only stock one master of each kind, and they will record it on the customer's tape for a fee (in an automatic vending machine, if desired).

ACKNOWLEDGMENT

L. Thunberg, S. Galus, and P. Padva, all of Armour Research Foundation, were helpful in the design, construction, and electronics, respectively, of the demonstration machine. A. Hultgren of American Molded Products made up the cartridges.

Correspondence

Method for Accurate Measurement of Tape Speed*

Some time ago, I approached the problem of determining, to a high degree of accuracy, the actual speed with which a piece of tape goes by a head assembly in a tape recorder.

Previous attempts by means of measuring a suitable length of tape and then measuring the amount of time required for this length to pass a given spot had left me with considerable misgivings as to the accuracy of the data. This misgiving arose, not only from the means of measuring the length of tape under proper tension, but also in deciding what that tension should be in view of themachine's characteristics.

The thought occurred to me that it is most desirable to measure the speed of the tape in the actual machine, using some dimension of the machine to provide the distance measurement. If I had two heads on a unit and could measure the distance between these two units, the interval between the passage of a mark over the first and then the second head should solve the problem.

On this basis, I arranged one of our standard tape transport machines with two heads whose distance I measured to an accuracy of something better than one part in a thousand. This was relatively easy to do by means of a height gauge and suitable accessories. With the tape stopped but in contact with a head, I made a magnetic mark by connecting an ohmmeter to the coil. On playing this mark, both heads gave essentially the same pulse once they had been aligned in azimuth. The outputs of these two heads were connected to an electronic counter through suitable amplifiers. The first head in the tape path was connected to the start input and the second connected to the stop input. After suitable adjustment of levels and other factors, quite reliable interval times were measured. The random variation on a low-flutter machine appeared to be in the order of 5 parts in 10,000. Knowing the distance and the time, it was then a simple matter to compute the speed.

Several pitfalls are to be avoided. The two heads must be aligned in azimuth before the distance between them is measured. The frequency response of the two heads should be essentially the same. It is important that the phasing of the two playback heads be the same in order that the additional delay, or lack thereof, resulting from phase reversal, will not be introduced.

It appears that the shortest and hence sharpest pulse is recorded with the tape stopped. This further avoids the necessity for generating a short pulse to be recorded.

The results of this when applied to a low-flutter machine (one having rms flutter in the order of 0.04 per cent) have been that we can make tapes having recorded thereon known wavelengths of high accuracy! These are quite useful in measuring the speed of production machines as well as for other purposes.

JOHN S. BOYERS
Manager, Engrg., Bell Sound Division
Thompson Ramo Wooldridge Inc.
Columbus, Ohio

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* Received by the PGA, January 15, 1960.

Comments on "Nonlinear Distortion Reduction by Complementary Distortion"*

Compensating distortion with complementary distortion[1] evidently can be accomplished for single frequencies; but once the nonlinearity that causes simple distortion has acted to produce modulation distortion, then restoration is impossible.

The situation is analogous to photography. Pincushion distortion could be compensated by rephotographing with a camera afflicted with barrel distortion, but if the original distortion were coma or simply out of focus, no restoration would be possible.

PAUL W. KLIPSCH
Klipsch and Associates
Hope, Ark.

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* Received by the PGA, February 2, 1960.

[1] J. Ross Macdonald, "Nonlinear distortion reduction by complementary distortion," IRE TRANS. ON AUDIO, vol. AU-7, pp. 128–133; September-October, 1959.

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On the "Insertion-Distortion Factor"*

In a recent paper[1] it has been shown how distortion generated by a nonlinear element can be reduced by insertion of a network having a complementary distortion along the transmission chain.

To evaluate the correction quantitatively, it may be useful to employ the "insertion-distortion factor," a quantity proposed in an earlier paper,[2] which may be defined:

a) Suppose that we have a transmission chain, at a certain point of which we will insert a two-terminal pair device. Then measure at this point, *before inserting* the device, the distortion factor as usual:

$$k_0 = \sqrt{\frac{\sum\limits_{n=2}^{\infty} V_n^2}{\sum\limits_{n=1}^{\infty} V_n^2}},$$

where V_n is the amplitude of the nth harmonic.

b) Measure again the total distortion factor k_t at the same point *after having inserted* the device. The difference,

$$k_i = k_t - k_0,$$

is the "insertion-distortion factor." It is evident that it depends not only on the two-terminal pair device itself, but also on the characteristics of the transmission chain. As it was pointed out,[2] "insertion-distortion factor" becomes negative if the inserted device compensates the pre-existing distortion, as in the case studied by Macdonald.

The "insertion-distortion factor" is also useful in characterizing distortion of quasi-linear two-terminal pair devices with comparatively low input and output impedences, when over-all harmonic distortion of the transmission chain is paramount. This is the case, *e.g.*, of transistor amplifiers used in carrier-frequencies systems.

VALERIO CIMAGALLI
Istituto Superiore delle Poste e delle Telecomunicazioni
Fondazione "Ugo Bordoni"
Rome, Italy

* Received by the PGA, January 25, 1960.

[1] J. Ross Macdonald, "Nonlinear distortion reduction by complementary distortion," IRE TRANS. ON AUDIO, vol. AU-7, pp. 128–133; September-October, 1959.

[2] V. Cimagalli, "Sulla distorsione non lineare dei transistori negli amplificatori per telecomunicazioni," Atti 5^ Rass. Internaz. Elettronica-Nucleare. Sez. Elettronica, Rome, Italy, pp. 109–128; 1958.

Contributors

J. J. BROPHY

James J. Brophy was born in Chicago, Ill., on June 6, 1926. He received the B.S.E.E. degree in 1947, the M.S. degree in physics in 1949, and the Ph.D. degree in physics in 1951, all from the Illinois Institute of Technology, Chicago.

He was on the faculty at Illinois Institute of Technology from 1949 to 1951, where he was also in charge of the electron microscope laboratory. In 1951, he joined the Armour Research Foundation, Chicago, Ill., where he has contributed to programs on magnetic devices, thin semiconducting films, transistors, semiconducting capacitors, infrared detectors, and other semiconductor problems. He has devoted major attention to fluctuation phenomena in solids. He is currently assistant director of physics research at Armour Research Foundation, directing research programs studying current noise in semiconductors, thermal and electrical properties of semiconductors at high impurity concentrations, gas discharge phenomena, fluctuations in ferromagnets, and magnetic recording.

Dr. Brophy is a member of the American Physical Society and Sigma Xi, and holds a number of patents on semiconductor and magnetic devices.

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Marvin Camras (S'41–A'42–SM'48–F'52), was born in Chicago, Ill., on January 1, 1916. He received the B.S.E.E. from Armour Institute of Technology, Chicago, Ill., in 1940, and the M.S. degree from Illinois Institute of Technology, Chicago, in 1942.

M. CAMRAS

Since 1940, as a member of the staff at Armour Research Foundation, he has done research on projects in the electronics department, including remote control, high-speed photography, magnetostriction oscillators, and static electricity. He has contributed developments which are used in modern magnetic tape and wire recorders, including high-frequency bias, improved recording heads, wire and tape materials, magnetic sound for motion pictures, multitrack tape machines, and stereophonic sound reproduction.

Mr. Camras is a Fellow of both the Acoustical Society of America and the AIEE, and is a member of SMPTE, AAAS, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He has held office as President of the IIT Chapter of Sigma Xi.

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D. F. ELDRIDGE

Donald F. Eldridge (A'50–M'55) was born on January 30, 1929, in Passaic, N. J. He received the B.S.E.E. degree from Lehigh University, Bethlehem, Pa., in 1949.

He then joined the Boeing Airplane Company, Seattle, Wash., where he engaged in work covering many phases of dynamic data acquisition and reduction. In 1956, he became affiliated with the Research Division of Ampex Corporation, Redwood City, Calif., where he has done research on many aspects of magnetic recording. He is presently head of the Magnetics Department of the Ampex Research Division.

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J. G. MCKNIGHT

John G. McKnight was born in Seattle Wash., on February 11, 1931. He received the B.S.E.E. degree from Stanford University, Stanford, Calif., in 1952.

In 1953, he worked for Ampex Corporation on the development of cinemascope-stereophonic sound equipment. He spent the years 1953 to 1956 in the U. S. Army, where he was assigned to the engineering staff of the Armed Forces Radio Service in New York. During this time, he also worked as development engineer for the Gotham and the Narma Audio Development Companies. He returned to Ampex in 1956, where he was a senior engineer in the Research Division until 1959, when he became manager of the Advanced Audio Section of the Professional Audio Division. He has always been interested in the problems of magnetic recording, specifically as they concern music, and has published several papers on this subject.

Mr. McKnight is a member of the Audio Engineering Society.

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