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TABLE OF CONTENTS

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The Editor's Corner

So Long

IT HARDLY SEEMS five years since we became *Editor* of these TRANSACTIONS. We never intended to stay so long, but it took more than three years to find someone else who was willing.

In keeping with the tradition of our predecessors, when a deadline approached and there was no material for the next issue, the *Editor* was obliged to go out and "make some news," write technical papers, or dash off a Guest Editorial. If there were no facts, we had to use fiction, and that's how some of our editorials grew. (No remarks about technical papers, please.)

Five years ago TRANSACTIONS was a struggling publication, frequently late. We are pleased to transfer it, in similar condition, to the able hands of Peter Tappan, with the consolation that there is still room for improvement.

For the many hours they devoted to TRANSACTIONS, when our *Associate Editors* could have been playing golf or something, we are grateful to Benjamin B. Bauer, Alexander Bereskin, William H. Ihde, J. Ross Macdonald, Daniel W. Martin, and Phillip B. Williams. We also appreciated the letters from our readers, who took time to praise or to criticize.

Goodbye, and it will be nice to come back occasionally as a guest.

—MARVIN CAMRAS

PTGA News

PTGA Directory

It is unlikely that you will ever need the information for a quiz show. But every once in a while you may be curious about certain things which can be found in our Directory PART II of this issue.

Besides yourself, are there any other dues-paying card-carrying PTGA members in your area? Look them up in the roster.

Why does someone else always get the PTGA Awards instead of you? Check the rules and send a letter to the Chairman.

Other interesting facts include historical data on Chapters and Committees, especially if your name is listed. The latest Constitution and Bylaws are there, if you ever want to prove a point.

In other words don't throw it away. The Directory might come in handy sometimes.

Special thanks are due to the PTGA staff who did more or less work in making this issue possible, and to E. K. Gannett and the IEEE Headquarters who compiled all the names and statistics.

Glossary of Organization Terminology for Engineers

Ben Miessner of Miami Shores, Fla., who sympathizes with engineers in adapting to the corporate environment, has sent the following glossary (author unknown).

Announcement: A public statement by an official of an organization, referring (but not restricted) to *facts* or *policies* (*q.v.*).

Crash Program: Overtime work made necessary by an error in *planning* (*q.v.*).

Commodity: (Aerospace Ind.) Engineering labor, bought from individuals by the week and resold to the Air Force by the hour, with added charges.

Challenging Opportunity: We got a contract.

Creative Climate: See *Challenging Opportunity.*

California Living: Driving to work on the freeway.

Dedicated: 1) Willing to make extraordinary efforts without special compensation or recognition, present or future; 2) Willing to accept responsibility without asking for the necessary authority; 3) Naive (said of employees).

Employee: A person who is paid for regular attendance at a designated place, rather than for the results he achieves.

Fact: A situation or condition which it is unnecessary to conceal, or which cannot be concealed.

Fees Paid by Employer: Cost is no object, because the employer is reimbursed by the Government.

Forecasting: Extrapolation.

Forecasting, Sales: Extrapolation modified by arbitrary assumptions.

Management: People whose compensation is related to the results that they produce.

Management Team: See *Team.*

Planning: Deciding how to cope with an unexpected situation.

Planning, Long-Range: Deciding how to cope with an unexpected situation that could have been foreseen.

Professional Man: A business man possessing a special license to sell certain services directly to the public, *e.g.* lawyer, hairdresser; eligible to join Rotary and other service clubs. No relation to *professional employee.*

Planning Committee: A number of employees who meet periodically to discuss *Planning* (*q.v.*), the final decision having been made beforehand by the General Manager.

Marketing: Every part of an industrial operation except financing, which can be performed by bankers, and manufacturing, which can be performed by job shops.

Modern Research Facility: A one-story, windowless building having landscaped grounds, located twenty miles from home and five miles from the nearest restaurant.

New Product: A modification of an old product, made to special order for a customer.

New Product Announcement: 1) An announcement of a *New Product* (*q.v.*); 2) A short published description of a device which is not in production, with a photograph of a mockup, used to assess the potential market.

Personnel Shortage: An expression denoting the desirability of being able to hire better engineers for less pay.

Professional Personnel: White-collar employees with college degrees. Also called *professional employees* (see *employee*).

Policy: Any of the basic rules of an organization, usually unpublished or secret, in order to avoid responsibility. A *Policy* can be deduced from observation of its effects, but is subject to change without notice.

Salary Commensurate with Ability: Pay based on number of years since graduation, according to a curve or chart.

Short-Term Situation: Present or impending financial trouble, usually followed by layoffs.

Team: A boss and one or more subordinates, to whom he parcels out parts of a job; a hierarchy.

The Engineer is Part of Management: The employee's outside interests and activities are subject to approval by the boss.

Voluntary Agreement: A document which a person must sign in order to get a job.

We are Expanding our Research Department: Earnings have been declining and we heard somewhere that this is supposed to help.

We're in Business to Make Money: We do not recognize that there is any difference between making lasers and making lawnmowers. —M. C.

Chapter News

On April 17, 1963, the Chicago Section of the PTGA, together with the Chicago Audio and Acoustical Group, met for their annual meeting at Allied Radio. Not only did they hear a fine paper, but again had the opportunity to see the modern facilities of this large electronic distributor. The feature of the program was a paper given by Ben Bauer, entitled "Some Techniques Toward Better Stereo-Sound." This talk included demonstrations of his measurement techniques, as well as introducing some new test records.

On May 29, 1963, the local section of PTGA met jointly with the Chicago Acoustical and Audio Group for their annual Ladies Night program. Over 80 men and women attended a champagne dinner and summer stock comedy play which followed. By keeping this program nontechnical, it was of great appeal to the women who attended.

Magnetic Recording Bibliography

A newly revised bibliography of magnetic recording, covering the years 1954–1961, is now available. It lists 762 papers and articles from 120 technical journals, and includes a cross index of authors and names and addresses of cited journals.

The bibliography was compiled by R. E. Hadady of the Kinelogic Corp. Copies may be obtained, at the price of $2.00, by writing to Kinelogic Corp., 29 South Pasadena Avenue, Pasadena, Calif.

On the Theories of AC Bias Used in Magnetic Tape Recording*

PAUL R. HINRICHS†

Summary—**This paper is concerned with experiments that were run for the purpose of supporting or discounting the various alternating current bias theories concerned with direct recording onto magnetic tape. Only the theories of Toomin and Wildfever, and Camras were found to be compatible with the results.**

Introduction

THE NUMBER of ac bias theories appearing in the literature is becoming formidable. Some of them exist solely for the purpose of explaining the ac bias phenomenon and are not compatible with existing facts. The author feels that it is important to understand the ac bias phenomenon if improvements in tape recordings are to be made which increase linearity or frequency response. For this reason, a series of experiments were run for the purpose of supporting or discounting the various theories. These experiments were run with considerable care; *e.g.*, when pulse-width modulation was used, there was almost no amplitude modulation. All current waveforms in the head were monitored with an oscilloscope to be sure that the current waveform had the correct shape. Seismic recording equipment was used in conjunction with Techno recording heads with 1-mil air gaps and with modified Techno playback amplifiers. The tape's speed was 3.6 inches per second and the bias frequency was 16 kc unless otherwise noted.

The material is presented in the same sequence in which the experiments were run since the results of one experiment often suggested a new experiment to follow.

AC Bias Theory and Experiments

Bedford[1] was one of the first to suggest that a PWM model would render plausible the linear amplitude characteristics of a biased recording; however, he gave no analytic proof that the model would in fact be linear. Sebestyen and Takacs[2] attempted a mathematical analysis, but this was shown to be incorrect;[3] *e.g.*, they predicted that the output should increase 6 db/octave with bias frequency, which is not the case.

The importance of determining the correctness of this theory is considerable because, if it is correct, then nonlinearities are a function of the bias waveform and not of the tape characteristics. Due to this importance, the model was analyzed to determine the relation between input and bias amplitude for a given output. Fig. 1 shows the input and output waveforms. The amplitude of the input and bias signals are a and b, respectively, while saturation has been arbitrarily made one. Note that the model is only assumed to be correct if the bias amplitude peaks exceed saturation. The output of an amplifier integrator should be proportional to the time the signal is in positive saturation minus the time that the signal is in negative saturation or

$$E_{\text{out}} \propto (\pi + \Delta\theta - \phi) - (\pi - \psi - \Delta\theta) \propto \frac{2\Delta\theta + \psi - \phi}{2}. \quad (1)$$

From Fig. 1 it is clear that, approximately,

$$\Delta\theta = \sin^{-1}\left(\frac{a}{b}\right)$$

$$\phi = \sin^{-1}\left(\frac{1-a}{b}\right)$$

$$\psi = \sin^{-1}\left(\frac{1+a}{b}\right).$$

Using a Taylor series, (1) becomes

$$E_{\text{out}} \propto \left(\frac{a}{b}\right)\left[\frac{1}{(1-b^{-2})^{1/2}} + 1\right] + \left(\frac{a}{b}\right)^3 \frac{1}{3!}\left[\frac{1+2b^{-2}}{(1-b^{-2})^{5/2}} + 1\right] + \left(\frac{a}{b}\right)^5 \frac{1}{5!}\left[\frac{6+51b^{-2}+24b^{-4}}{(1-b^{-2})^{9/2}} + 6\right] + \cdots \quad (2)$$

For $a \ll b$ the results indicate that the recording process should be linear. The model also explains the increase in amplification first pointed out by Carlson and Carpenter[4] since the signal amplitude does not have to be too large to leave the tape completely saturated in one direction.

Eq. (2) suggests a simple check on this theory; *viz.*, hold the output constant and compare plots of a vs b of the experimental and calculated values. This was done

* Received March 25, 1963. Part of the data used in this paper was provided through the courtesy of the Califorina Research Corporation, La Habra, Calif.

† General Dynamics, Fort Worth, Tex.

[1] L. H. Bedford, "Magnetic tape recording," *Electronic Radio Engr.*, vol. 36, pp. 320–322; September, 1959.

[2] L. G. Sebestyen and J. Takacs, "Magnetic recording theory of tape magnetization," *Electronic Tech.*, vol. 38, pp. 274–278; August, 1961.

[3] R. Langmaid and R. Noble, "Magnetic recording," *Electronic Tech*, vol. 38, pp. 381–382; September, 1961.

[4] W. L. Carlson and G. W. Carpenter, "Radio telegraph system," U. S. Patent No. 1,640,881; August 30, 1927.

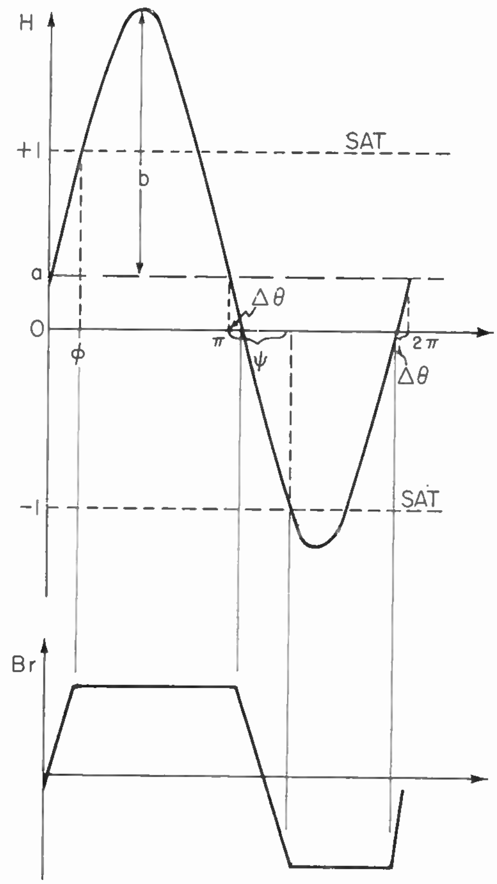

Fig. 1. Input (top) and output (bottom) for one cycle of bias.

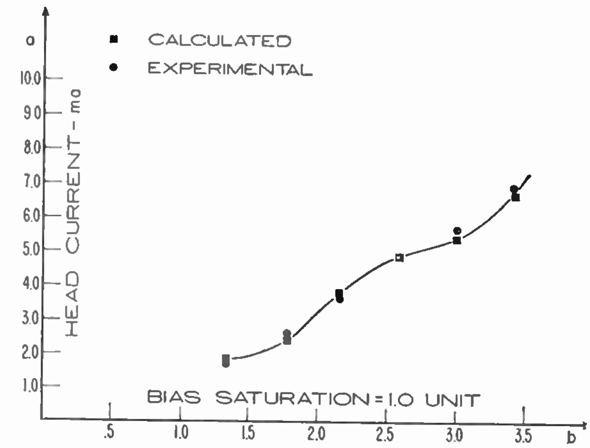

Fig. 2—Graph of a vs b with constant output for the 3M122 magnetic tape.

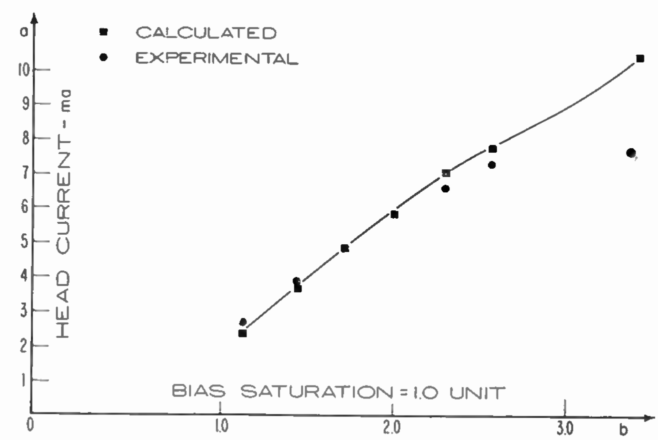

Fig. 3—Graph of a vs b with constant output for the Indel GEP magnetic tape.

and the results are shown in Figs. 2 and 3 for two different tapes which show that there is enough correlation to warrant further investigation.

At this point, it was decided to use a square-wave bias signal with a sinusoidal input signal which should produce no modulation at all as long as the signal peaks were well into saturation. However, modulation was observed. In fact, the output was the same as for sinusoidal bias when the peak amplitudes of the bias signals were the same. Also, the same result was observed using a triangular bias waveform. Total distortion was less than five per cent in all three cases.

This theory rested on the assumption that the signal placed on tape depended only upon the value of the tape's magnetization as the tape passed the leading edge of the head gap. This assumption is apparently incorrect.

Since other theories[5] explain the results of ac bias phenomenon with a form of PWM, it was decided to build a system where only PWM occurred. That is, only the width of a square-wave bias input signal would be varied and again the output would be proportional to the time in positive saturation minus the time in negative saturation. The frequency of the "bias" input signal was chosen to be 10 kc, which would not pass through the system. The waveforms for a sinusoidal input are shown in Fig. 4. The result was that no output appeared. Note that if the "bubble" theory of Bauer and Mee were a correct explanation of ac bias theory, then modulation would have appeared since the assumption was made that there is a positive and negative sphere of influence that changes on each half-cycle. In their model the sphere of influence changed due to the difference in the absolute amplitudes of the positive and negative peaks while here the sphere of influence changes due to the tape moving past the head. That is, if the tape is in positive saturation for a longer duration than in negative saturation, then the net flux will be positive. Also, if the "bubble" model were correct, then there would exist a maximum bias frequency for a particular input level which if exceeded would cause the tape to stay in saturation, since the bubble with the larger radius would override the effects of the bubble with the smaller radius during succeeding half-cycles. This occurs when $vT/2 < \Delta R$ where v is the tape's velocity, T is the period of the bias signal and ΔR is the

[5] B. B. Bauer and C. D. Mee, "A new model for magnetic recording," IRE Trans. on Audio, vol. AU-9, pp. 139–145; September–October, 1961.

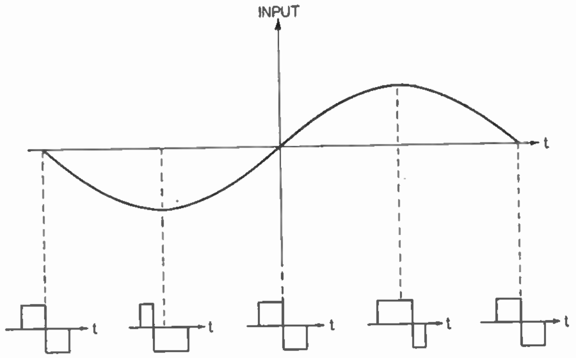

Fig. 4—Bias waveforms (bottom) for sinusoidal input signal (top).

difference between the bubble's radii for succeeding half-cycles. An experiment was run with a bias frequency such that a discontinuity should have been observed if ΔR were greater than 2×10^{-6} inches; however, normal modulation was observed with less than three per cent distortion. It should be pointed out that although the "bubble" theory fails to explain the ac bias phenomenon, it does illustrate correctly the low-frequency recording process without bias.

So far, two important facts have been illustrated by these experiments:

1) AM varies as the peaks of the bias signal are varied and it is independent of the bias waveform.
2) AM does not depend upon PWM of the bias signal to work.

Next, experiments were run to find out if the bias signal was recorded. This was done first by developing the tape with magnetic filings which showed no trace of the bias signal. Another test was also easy to make. It was observed that the wide-band noise output of the amplifier integrator vs an input dc recorded signal (no bias) was as shown by the solid line in Fig. 5. Now, if the bias alone were recorded, a net increase would have been expected in the noise output, but this was not the case. When a dc current was applied with bias, the dotted curve as shown in Fig. 5 was observed, indicating that the dc signal was recorded.

One last experiment was run to insure that there was no necessity of recording the bias signal. This was done by using a bias signal whose frequency was such that there were approximately two complete wavelengths of bias signal per the length of a domain. In our case, the bias frequency used was 80 kc. The result was that normal ac bias recordings were made with total distortions of less than three per cent.

The results of these last three experiments indicate that the bias signal is not recorded and in no way depends upon its being recorded. Thus, Zenner's theory[6] has been discounted since he assumed that the bias signal was recorded.

[6] R. E. Zenner, "Magnetic recording with ac bias," Proc. IRE, vol. 39, pp. 141–146; February, 1951.

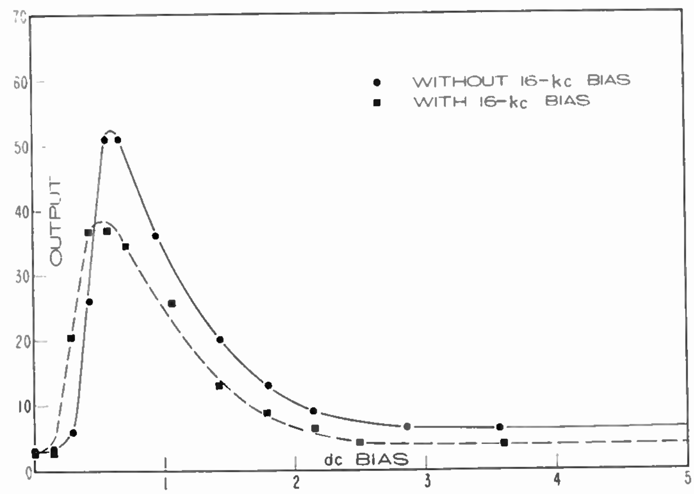

Fig. 5.—Tape noise vs dc bias for the 3M122 tape.

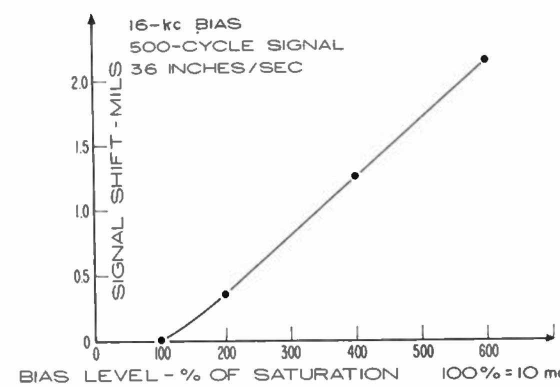

Fig. 6—Recording phase shift vs bias using the 3M122 tape.

Toomin and Wildfever,[7] and Camras[8] have presented explanations for ac bias theory that are not contradictory to the experiments. In fact, Toomin and Wildfever have illustrated that any residual flux B_r can be obtained with a decaying field which actually depends only upon the maximum and minimum excursions by the simple expedient of keeping B_r within the interior of each subloop. Thus, they have shown that a decaying field can produce any residual flux distribution. It is too bad that their theory does not readily yield to mathematical analysis for this would indicate which qualities of the magnetic tape to look for in order to improve it. Also, it is contemporary to accept theories that yield to mathematical analysis and sometimes without enough thought as to their validity.

There is a simple experiment that can be run to test the validity of the theories of Toomin and Wildfever, and Camras. If the bias peaks are large enough to saturate the tape (which is the normal operating procedure),

[7] H. Toomin and D. Wildfever, "The mechanism of supersonic frequencies as applied to magnetic recording," Proc. IRE, vol. 32, pp. 664–668; November, 1944.

[8] M. Camras, "Methods and means of magnetic recording," U. S. Patent No. 2,351,004; May 30, 1944.

then the point at which the tape starts to approach its final value is not directly beneath the head gap. In fact, if the bias level is increased, it should be possible to shift the signal up the tape. Two channels were first recorded simultaneously on a single tape and their relative phases were noted. The bias level on one was then increased, which did cause the signal to shift almost linearly with the applied bias. This signal shift vs bias level is shown in Fig. 6. This same reasoning would indicate that the high-frequency response should decrease as the bias level is increased. This has been observed by Daniel[9] and others.

Conclusion

New theories to illustrate ac bias should be carefully scrutinized and should do more than just explain the linearizing process inherent in ac bias recordings. In most cases experiments can be thought of and run which will either strongly support or strongly discount each one. Eldridge's theory[10] is just such an example, for his model predicts modulation when PWM of the bias signal is used and this is not consistent with the experimental results.

These experiments strongly support the theory of Toomin and Wildfever, and Camras. This is important because it points out that the nonlinearities are due to the inherent magnetic properties of the tape. For improvement one must either look for a tape that has a more linear transfer characteristic or change recording tactics, *e.g.*, predistort the recording signal with a compensating nonlinearity to linearize the over-all transfer characteristic.

[9] D. Daniel, "The influence of some head and tape constants on the signal recorded on a magnetic tape," Proc. IEEE, vol. 100, pt. III, pp. 168–175; May, 1953.

[10] D. F. Eldridge, "The mechanism of ac biased magnetic recording," IRE Trans. on Audio, vol. AU-9, pp. 155–158; Septembel–October, 1961.

A Theoretical Treatment of Self-Demagnetization in Magnetic Recording*

R. G. BAYER†

Summary—**A model for self-demagnetization is proposed which states that the value of the field and magnetization at every point in the material represent a point on a particular hysteresis loop of the material. This loop can either be a major or a minor loop of the material. The particular loop ascribed to a point is determined by the magnetization which existed at that point initially. This model has been applied to an ideal case of longitudinal recording. The results are compared with the Kostyshyn model for self-demagnetization and with experimental data.**

Introduction

The phenomenon of self-demagnetization in magnetic recording may be described in the following manner. In the write process a small element of magnetic material will eventually go from an initial state a (Fig. 1) to a state b as it moves to the vicinity of the write head, is written on, and moves away from the vicinity of the head. After point b, the magnetization of that element will be governed by the fields produced by the magnetization in the tape. These fields will be opposite in sign to the magnetization, and will tend to decrease the magnitude of the magnetization for that element until an equilibrium state c is reached. This decrease in magnetization by the field produced by the magnetization is known as self-demagnetization and the resulting equilibrium state may be termed the self-demagnetized state.

This phenomenon occurs in permanent magnets and has been treated in that case in terms of demagnetization factor.[1] This factor is essentially the ratio of the field to the magnetization which occurs in the equilibrium state. It depends only on the geometry of the magnet and has been determined exactly for ellipsoids and approximately for bar and rods.[2]

In magnetic recording, self-demagnetization was treated in terms of a demagnetization factor first by Westmijze[3] and later by Kostyshyn.[4] Westmijze con-

* Received March 4, 1963.
† General Products Division, IBM Corporation, Endicott, N. Y.

[1] R. M. Bozorth, "Ferromagnetism," D. Van Nostrand Company, Inc., Princeton, N. J., p. 10; 1956.
[2] *Ibid.*, pp. 845–849.
[3] W. K. Westmijze, "Studies on Magnetic Recording," *Philips Res. Rept.*, vol. 8, pp. 245–269; 1953.
[4] B. Kostyshyn, "A harmonic analysis of saturation recording in a magnetic medium," 1961 IRE International Convention Record, pt. 2, pp. 112–127.

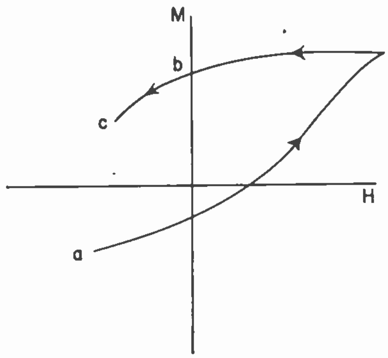

Fig. 1—Magnetic recording process.

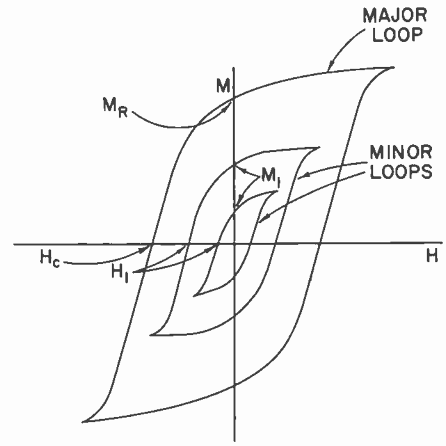

Fig. 2—Family of hysteresis loops.

siders only sine-wave magnetization, while Kostyshyn considers any periodic function which could be expanded into a Fourier Series. Westmijze concluded that the use of a demagnetization factor was not entirely satisfactory since the functional behavior with respect to depth in the magnetic medium was not the same for the field and the magnetization; consequently, the ratio was not a constant. Kostyshyn remedied this by considering an average demagnetization factor (average over the thickness of the magnetic medium). However, in his work he utilized a superposition principle in describing an irreversible and nonlinear process.

The model presented here does not utilize either the concept of a demagnetization factor or the concept of superposition. In addition the problem of self-demagnetization is treated in a nonlinear manner. This model does, however, imply the assumption that hysteresis loops can be used to describe the behavior of small elements of magnetic material. The assumption appears to be reasonable if the elements which need to be treated are larger than a domain. In this case then, the hysteresis loop can be thought of as representing the average behavior of the element. The validity of such an assumption will be determined by the results obtained from the model.

Model

The model assumes that a magnetic material possesses a family of hysteresis loops of the type indicated in Fig. 2. These loops can be specified in terms of their remanent magnetization M_1 (the magnetization occurring at zero field). The major loop is the saturated hysteresis loop, *i.e.*, the remanent magnetization of the major loop is equal to the remanent magnetization of the material M_R. The minor loops are the unsaturated loops and their value of remanent magnetization is smaller than M_R, *i.e.*, $M_1 < M_R$.

In this proposal the model states that in the self-demagnetized state the value of the field and the magnetization occurring in every element of the material must represent a point on an appropriate hysteresis loop of the type mentioned previously. The appropriate loop for each element is that loop whose remanent magnetization is equal to the magnetization which that element possessed as it passed through state *b*.

According to the model, the general scheme for determining the magnetization in the self-demagnetized state is to assume a distribution with respect to space coordinates for the magnetization occurring in state *b* and to assume certain properties of the hysteresis loops of the material. Under these two conditions, a magnetization in the self-demagnetized state M is to be determined such that the magnetization and the field H (which the magnetization produces) in each element of the medium represent a point on the particular loop assigned to that element.

The model is not concerned with the specific means by which the magnetization at *b* can be determined from the magnetization at *a*. This can be determined (Fig. 1) by a theory proposed by Ku.[5] It concerns itself only with the transition from *b* to *c*.

The model is applied below to a longitudinal system of recording to demonstrate the model and to investigate the validity of the model.

Formulation

The procedure used in formulating the model is to first assume an expression for the major and minor hysteresis loops in terms of the initial conditions. Expressions are then assumed for the initial and final values of the magnetization and the field in the tape. The expression for the initial values are fully specified and those for the final values, *i.e.*, the values in the self-demagnetized state, are only partially specific. In the latter case only the dependency on the spatial coordinates are specified and certain constants are left unspecified. When these constants are determined, the solution of the problem will be determined.

The values of these constants are determined by substituting the expression for the initial and final values of

[5] T. C. Ku, "An analytical expression for describing the write process in magnetic recording," Proc. IRE (*Correspondence*), vol. 49, pp. 1337–1338; August, 1961.

the magnetization and field into the expression for the hysteresis loops and solving the resulting expression for these constants.

It is assumed that the portion of the M-H loops occurring in the second and fourth quadrants may be represented by rectangular hyperbolas of the following form.

$$M = \frac{M_1 M_2(H - H_1)}{(2M_2 - M_1)H - M_2 H_1}. \quad (1)$$

In this equation M_1 is the remanent magnetization of the loops, H_1 is the coercive force of the loops (the value of the field at zero magnetization), and M_2 is the value of M at $H_1/2$.

The approximation of hysteresis loops by rectangular hyperbolas has been known and used for some time.[4,6] The tape[7] used for obtaining the experimental data obeys this relationship quite well (Fig. 3).

The parameters M_1, H_1 and M_2 are not independent in a given material; any two can be given in terms of the third. For the model discussed in this paper, it is useful to have H_1 and M_2 expressed in terms of M_1. For the tape used, these relationships may be expressed as follows:

$$|H_1|^2 = \frac{|H_c|^2}{|M_R|} |M_1| \quad (2)$$

where H_c and M_R are respectively the coercive force and the remanent magnetization of the major loop of the material.

$$M_2 = \frac{|M^1|}{|M_R|} M_1 \quad (3)$$

where M' is the value of M_2 for the major loop. These relationships were determined from experimental data; agreement between these expressions and experimental data is shown in Fig. 4.

A magnetic media of infinite length and width and of thickness d is assumed. Magnetization is assumed to be periodic of wavelength λ. All coordinates are normalized with respect to λ, hence the thickness of the medium in normalized coordinates is d/λ. The coordinate along the length of the media is x and along the thickness is y, $(x, 0)$ is a point on the upper surface of the media and $(x, -d/\lambda)$ is a point on the lower surface.

Depending on their origin, the self-demagnetizing fields produced in such a system may be separated into two types. One type is the result of the change of magnetization in the media; the other is the result of the poles which tend to be produced on the upper and lower boundaries of the media when any fields or magnetization are present in the y direction. In this analysis the first type will be considered. The effect due to the second may be taken into account by considering the material to be anisotropic. That is, the hysteresis loop in the y direction is a sheared hysteresis loop, while that in the x direction is an unsheared loop, or normal (Fig. 5). For $d/\lambda \ll 1$, this anisotropy is very great and the magnetization produced in the y direction by any fields in that direction can be ignored when compared to the magnetization which would be produced by that same field when applied in the y direction.

[6] Bozorth, *op. cit.*, pp. 349–351.
[7] 3M109 Red Oxide Tape.

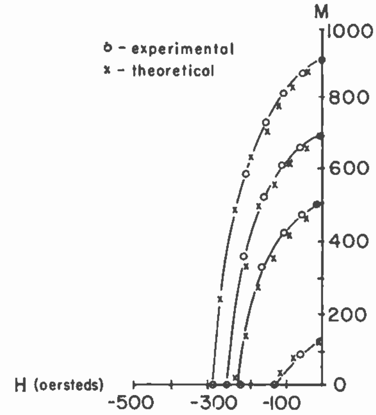

Fig. 3—Demagnetization portion of a hysteresis loop.

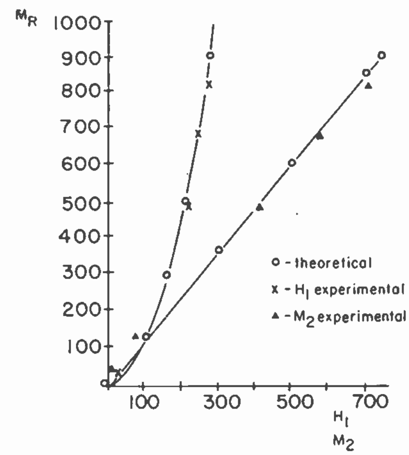

Fig. 4—$|M_2|$ and $|H_1|$ as a Function of $|M_R|$.

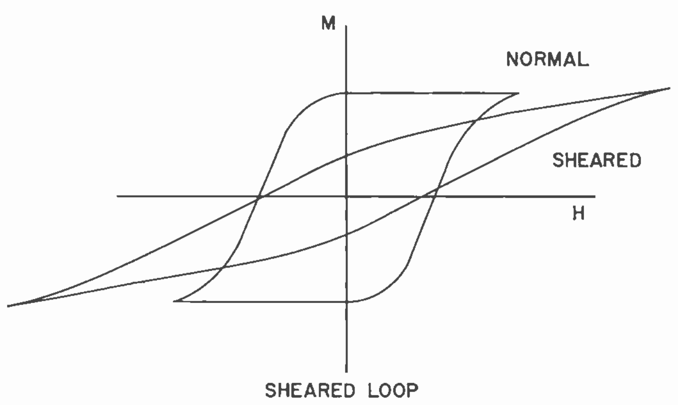

Fig. 5—Sheared loop.

For this reason the magnetization is assumed to be purely longitudinal. In addition, for simplicity, no dependency of y is considered in this study.

It is assumed that M_1, M_2, and H_1 can be expressed as follows:

$$M_1 = \sum_{s=1}^{m} \alpha_s \sin 2s\pi x \tag{4a}$$

$$M_2 = \sum_{r=1}^{m} \beta_r \sin 2r\pi x \tag{4b}$$

$$H_1 = \sum_{t=1}^{m} \gamma_t \sin 2t\pi x \tag{4c}$$

where $\alpha_1, \alpha_2, \cdots, \alpha_m; \beta_1, \beta_2, \cdots, \beta_m; \gamma_1, \gamma_2, \cdots, \gamma_m$ are the first m coefficients of a Fourier expansion of M_1, M_2, and H_1 respectively. The β's and γ's can be expressed in terms of the α's. An exact form of this relationship will be given later.

It is assumed that the magnetization and the field in the x direction in the self-demagnetized state can be expressed as follows:

$$M = \sum_{k=1}^{m} a_k \sin 2k\pi x \tag{5a}$$

$$H = \sum_{l=1}^{m} b_l \sin 2l\pi x \tag{5b}$$

where the a_k's are the unknowns to be determined, and the b_e's are a function of the a_k's. This relationship will also be given later.

According to theory, M and H must represent a point on the loop specified by M_1, M_2, and H_1; *i.e.*, (1) must be identically true for every value of x and y. Substituting the expression for M_1, M_2, etc. into (1) leads to the following identity whose solution will yield the values of the a_k's.

$$\sum_{r=1}^{m}\sum_{n=1}^{m}\sum_{l=1}^{m}\{(2\beta_r - \alpha_r)a_n b_l - \beta_r\gamma_l a_n - \alpha_r\beta_n b_l + \alpha_r\beta_n\gamma_l\}$$

$$\sin 2r\pi x \sin 2n\pi x \sin 2l\pi x \equiv 0. \tag{6}$$

It can be shown that

$$\sin n\phi = n \sin\phi\left[1 + \sum_{s=1,2,3}^{(n-1)/2}\left(\sum_{r=0,1,2}^{s}\right)B_0{}^1(n, s)\cos^{2r}\phi\right],$$

where n is odd (7a)

$$\sin n\phi = n\sin\phi\left[\cos\phi + \cos\phi\sum_{s=1,2,3}^{(n-2)/2}\sum_{r=0,1,2}^{s}\right.$$

$$\left.\cdot B_e{}^1(n, s)\cos^{2r}\phi\right],\quad n \text{ even} \tag{7b}$$

where

$$B_0{}^1(n, s) = (n^2 - 1^2)(n^2 - 3^2)\cdots (n^2 - [2s-1]^2)(-1)^{s+r}{}_sC_r$$

$$n = 1, 3, 5\cdots; s = 1, 2, 3, \cdots, \frac{n-1}{2}$$

$$B_e{}^1(n, s) = (n^2 - 2^2)(n^2 - 4^2)\cdots (n^2 - 4s^2)(-1)^{s+r}{}_sC_r$$

$$n = 2, 4, 6\cdots; s = 1, 2, 3\cdots, \frac{n-2}{2}.$$

If (6) is placed in the following form,

$$\left\{\sum_{r=1,3}^{m_1} + \sum_{r=2,4}^{m_2}\right\}\left\{\sum_{n=1,3}^{m_1} + \sum_{n=2,4}^{m_2}\right\}\left\{\sum_{l=1,3}^{m_1} + \sum_{l=2,4}^{m_2}\right\}\cdot F(r, n, l) \tag{8}$$

$$\cdot \sin 2r\pi x \sin 2n\pi x \sin 2l\pi x \equiv 0$$

where

$m_1 = m;\quad m_2 = m - 1;\quad$ if m is odd;

$m_2 = m;\quad m_1 = m - 1;\quad$ if m is even

and where

$$F(r, n, l) = (2\beta_r - \alpha_r)a_n b_l - \beta_r\gamma_l a_n - \alpha_r\beta_n b_l + \alpha_r\beta_n\gamma_l,$$

and (7) is substituted, the following is arrived at upon reduction:

$$\sum_{r=1,3}^{m_1}\sum_{n=1,3}^{m_1}\sum_{l=1,3}^{m_1} F(r, n, l)rnlL_0(r)L_0(n)L_0(l)$$
$$+ \sum_{r=1,3}^{m_1}\sum_{n=1,3}^{m_1}\sum_{l=2,4}^{m_2} F(r, n, l)rnlL_0(r)L_0(n)L_e(l)$$
$$+ \sum_{r=1,3}^{m_1}\sum_{n=2,4}^{m_2}\sum_{l=1,3}^{m_1} F(r, n, l)rnlL_0(r)L_e(n)L_0(l)$$
$$+ \sum_{r=1,3}^{m_1}\sum_{n=2,4}^{m_2}\sum_{l=2,4}^{m_2} F(r, n, l)rnlL_0(r)L_e(n)L_e(l)$$
$$+ \sum_{r=2,4}^{m_2}\sum_{n=1,3}^{m_1}\sum_{l=1,3}^{m_1} F(r, n, l)rnlL_e(r)L_0(n)L_0(l)$$
$$+ \sum_{r=2,4}^{m_2}\sum_{n=1,3}^{m_1}\sum_{l=2,4}^{m_1} F(r, n, l)rnlL_e(r)L_0(n)L_e(l)$$
$$+ \sum_{r=2,4}^{m_2}\sum_{n=2,4}^{m_2}\sum_{l=1,3}^{m_1} F(r, n, l)rnlL_e(r)L_e(n)L_0(l)$$
$$+ \sum_{r=2,4}^{m_2}\sum_{n=2,4}^{m_2}\sum_{l=2,4}^{m_2} F(r, n, l)rnlL_e(r)L_e(n)L_e(l) \equiv 0, \tag{9}$$

where

$$L_0(t) = 1 + \sum_{s=1,2,3}^{(t-1)/2}\sum_{k=0,1,2}^{s} B_0^1(t, s)\cos^{2k} 2\pi x,$$

and

$$L_e(t) = \cos 2\pi x + \cos 2\pi x \cdot \sum_{s=1,2,3}^{(t-2)/2}\sum_{k=0,1,2}^{s} B_e{}^1(t, s)\cos^{2k} 2\pi x.$$

The solution of this identity in (8) will, in general, yield a system of simultaneous equations involving the a_k's and the b_l's. The exact nature of these equations with regard to the unknowns (a_k's) may be determined by explicitly obtaining the b_l's as a function of the a_k's. This is done by solving Maxwell's equation for magnetic media with magnetization given by (5a) in free space.

In the case of magneto-statics, Maxwell's Equations reduce to the following:

$$\nabla \times H = 0 \qquad (10a)$$

$$\nabla \cdot B = 0 \qquad (10b)$$

where

$$B = H + M.$$

These three expressions may be combined to yield the following equation:

$$\nabla^2 H = -\nabla(\nabla \cdot M). \qquad (11)$$

Now the magnetizations in the three regions (in, above, and below the tape) may be written as follows:

$$M = 0, \qquad -\infty \leq y \leq -\frac{d}{\lambda}, \quad 0 \leq y \leq \infty \qquad (12a)$$

$$M = i \sum_{k=1}^{m} a_k \sin 2k\pi x, \qquad -\frac{d}{\lambda} \leq y \leq 0 \qquad (12b)$$

and, consequently,

$$\nabla \cdot M = 0, \qquad -\infty \leq y \leq -\frac{d}{\lambda}, \quad 0 \leq y \leq \infty \qquad (13a)$$

$$\nabla \cdot M = \sum_{k=1}^{m} 2k\pi a_k \cos 2k\pi x, \qquad \frac{-d}{\lambda} \leq y \leq 0. \qquad (13b)$$

Substituting (13) into (11) and reducing, the following pairs of equations are obtained:

$$\left.\begin{aligned} \nabla^2 H_x &= 0 \\ \nabla^2 H_y &= 0 \end{aligned}\right\} \qquad -\infty \leq y \leq \frac{-d}{\lambda} \quad (14a), \qquad 0 \leq y \leq \infty \quad (14a')$$

$$\left.\begin{aligned} \nabla^2 H_x &= \sum_{k=1}^{m} (2k\pi)^2 a_k \sin 2k\pi x \\ \nabla^2 H_y &= 0. \end{aligned}\right\} \qquad \frac{-d}{\lambda} \leq y \leq 0. \quad (14b), (14b')$$

The fields must satisfy the following additional conditions:

1) Periodic in x.
2) When $M=0$, $H=0$.
3) $\nabla \cdot B = \nabla \cdot (H+M) = 0$.
4) At $y = \pm\infty$, $H=0$.
5) At $y=0$ and $y=-d/\lambda$, B_y and H_x must be continuous.

Utilizing these conditions and standard separation of variable technique,[8] the following expressions result:

$$H = i\left\{\sum_{l=1}^{m} \frac{a_l}{2}\left(e^{(-2l\pi d)/\lambda}-1\right)e^{-2l\pi y} \sin 2l\pi x\right\} + j\left\{\sum_{l=1}^{m} \frac{a_l}{2}\left(e^{(-2l\pi d)/\lambda}-1\right)e^{-2l\pi y} \cos 2l\pi x\right\} \qquad y \geq 0 \qquad (15a)$$

$$H = i\left\{\sum_{l=1}^{m}\left(\frac{a_l}{2} e^{(-2l\pi d)/\lambda}e^{-2l\pi y} + \frac{a_l}{2} e^{-2l\pi y} - a_l\right) \sin 2l\pi x\right\} + j\left\{\sum_{l=1}^{m}\left(\frac{a_l}{2} e^{(-2l\pi d)/\lambda}e^{-2l\pi y} - \frac{a_l}{2} e^{-2l\pi y}\right) \cos 2l\pi x\right\} \qquad 0 \geq y \geq \frac{-d}{\lambda} \qquad (15b)$$

$$H = i\left\{\sum_{l=1}^{m} -\frac{a_l}{2}\left(e^{(2l\pi d)/\lambda}-1\right)e^{2l\pi y} \sin 2l\pi x\right\} + j\left\{\sum_{l=1}^{m} \frac{a_l}{2}\left(e^{(2l\pi d)/\lambda}-1\right)e^{2l\pi y} \cos 2l\pi x\right\} \qquad y \leq \frac{-d}{\lambda}. \qquad (15c)$$

The x component of the field in the tape is seen to be a function of y (15b). However, since the dependency is not a strong one for $d/\lambda \ll 1$, an average value is satisfactory for H.

$$H = \frac{\displaystyle\int_{-d/\lambda}^{0} \sum_{l=1}^{m} \frac{a_l}{2}\left[e^{(-2l\pi d)/\lambda}e^{-2l\pi y}+e^{2l\pi y}-2\right] \sin 2l\pi x\, dy}{\displaystyle\int_{-d/\lambda}^{0} dy}. \qquad (16)$$

This reduces to

$$H = \sum_{l=1}^{m} A_l a_l \sin 2l\pi x, \qquad (17)$$

where

$$A_l = \frac{\lambda}{d^2 l\pi} - \frac{\lambda}{d^2 l\pi} l - \frac{2l\pi d}{\lambda} - 1.$$

Hence

$$b_l = A_l a_l. \qquad (18)$$

If (18) is substituted into the expression for $F(r, n, l)$ (8), $F(r, n, l)$ is seen to be quadratic in the unknown a_k's. Hence the set equations obtained from the identity given in (9) is a system of quadratic equations, the solution of which will yield the values of the a_k's.

In the ideal case, m is infinite and there are an infinite

[8] See for example, H. Margenau and G. Murphy, "The Mathematics of Physics and Chemistry," D. Van Nostrand Company, Inc., Princeton, N. J.; 1953.

number of quadratic equations involving an infinite number of unknowns. This case is not solved directly. Instead, the existence of a solution for that case is indicated by obtaining a series of solutions for different values of m and showing that the same solution occurs for successive values of m.

Solution

It is convenient to assume at this point that the even harmonic terms in the expansion for M_1, M_2, H_1, M, and H are zero. This will be true for a square wave, trapezoidal or any other initial magnetization in which each half-cycle is symmetric about its midpoint.[9] In such cases, therefore, m need only be taken as odd. The identity given in (11) then reduces to

$$\sum_{r=1,3}^{m} \sum_{n=1,3}^{m} \sum_{l=1,3}^{m} F(r, n, l) rnl L_0(r) L_0(n) L_0(l) \equiv 0. \tag{19}$$

When $m=1$, only one equation results from the reduction of the identity given in (19). It is

$$(2\beta_1 - \alpha_1) A_1 a_1^2 - (\beta_1\gamma_1 + \alpha_1\beta_1 A_1) a_1 + \alpha_1\beta_1\gamma_1 = 0. \tag{20}$$

When $m=3$, the following set results:

$$\begin{aligned} K_{11}A_1a_1^2 + K_{12}A_3a_3^2 - K_{11}(A_3 + A_1)a_1a_3 \\ + (K_{13} + K_{14}A_1)a_1 \\ + (K_{15} + K_{16}A_3)a_3 + K_{17} = 0 \end{aligned} \tag{21a}$$

$$\begin{aligned} K_{21}A_1a_1^2 - 2K_{12}A_3a_3^2 + K_{22}(A_3 + A_1)a_1a_3 \\ + (K_{23} + K_{24}A_3)a_3 + (K_{25} + K_{26}A_1)a_1 \\ + K_{27} = 0 \end{aligned} \tag{21b}$$

$$\begin{aligned} K_{12}A_3a_3^2 + K_{21}(A_3 + A_1)a_1a_3 + (K_{31} + K_{32}A_3)a_3 \\ + (K_{33} + K_{34}A_1)a_1 + K_{35} = 0 \end{aligned} \tag{21c}$$

$$K_{21}A_3a_3^2 + (K_{33} + K_{34}A_3)a_3 + K_{41} = 0, \tag{21d}$$

where the K's are functions of α_1, α_3, β_1, β_3, γ_1, and γ_3 (Table I). For higher values of m, similar sets of equations would be obtained. For $m=5$, seven quadratic equations in terms of the three unknowns, a_1, a_3, a_5, would be obtained.

An examination of the sets of equations obtained in this fashion would show that as m increases the number of equations also increases. Equations which existed for a lower value of m reappear for higher values of m with the addition of new terms and with modified constants. These modifications of the equations with increasing m can be thought of as improving the approximation to the case where m is infinite by inclusion of higher-order terms. For example, the coefficient of α_1^2 in (20) ($m=1$) is $(2\beta_1-\alpha_1)\ A_1$; in (21a) ($m=3$), it is $[(2\beta_1-\alpha_1)-(2\beta_3-\alpha_3)]\ A_1$. If one assumes that Fourier coefficients decrease with increasing indices, then the coefficient of A_1 in the second expression is improved over the first expression by inclusion of the second-order term, $(2\beta_3-\alpha_3)$. This is likewise true for the introduction of terms involving α_3 into (20) which becomes (21a) after the introduction.

TABLE I

$$\begin{aligned}
K_{11} &= (2\beta - \alpha_1) - (2\beta_3 - \alpha_3) \\
K_{12} &= (2\beta_1 - \alpha_1) \\
K_{13} &= -\beta_1\gamma_1 + \beta_1\gamma_3 + \beta_3\gamma_1 - \beta_3\gamma_3 \\
K_{14} &= -\alpha_1\beta_1 + \alpha_1\beta_3 + \alpha_3\beta_1 - \alpha_3\beta_3 \\
K_{15} &= \beta_1\gamma_1 - \beta_1\gamma_3 - \beta_3\gamma_1 \\
K_{16} &= \alpha_1\beta_1 - \alpha_1\beta_3 - \alpha_3\beta_1 \\
K_{17} &= \alpha_1\beta_1\gamma_1 - \alpha_1\beta_1\gamma_3 - \alpha_1\beta_3\gamma_1 + \alpha_1\beta_3\gamma_3 - \alpha_3\beta_1\gamma_1 + \alpha_3\beta_1\gamma_3 + \alpha_3\beta_3\gamma_1 \\
K_{21} &= +2\beta_3 - \alpha_3 \\
K_{22} &= (2\beta_1 - \alpha_1) - 2(2\beta_3 - \alpha_3) \\
K_{23} &= -\beta_1\gamma_1 + 2\beta_1\gamma_3 + 2\beta_3\gamma_1 \\
K_{24} &= -\alpha_1\beta_1 + 2\alpha_1\beta_3 + 2\alpha_3\beta_1 \\
K_{25} &= -\beta_3\gamma_1 + 2\beta_3\gamma_3 - \beta_1\gamma_3 \\
K_{26} &= -\alpha_3\beta_1 + 2\alpha_3\beta_3 - \alpha_1\beta_3 \\
K_{27} &= \alpha_1\beta_1\gamma_3 - 2\alpha_1\beta_3\gamma_3 - 2\alpha_3\beta_1\gamma_3 + \alpha_3\beta_1\gamma_1 - 2\alpha_3\beta_3\gamma_1 + \alpha_1\beta_3\gamma_1 \\
K_{31} &= \beta_1\gamma_3 - \beta_3\gamma_1 \\
K_{32} &= -\alpha_1\beta_3 - \alpha_3\beta_1 \\
K_{33} &= -\beta_3\gamma_3 \\
K_{35} &= \alpha_1\beta_3\gamma_3 + \alpha_3\beta_1\gamma_3 + \alpha_3\beta_3\gamma_1 \\
K_{41} &= \alpha_3\beta_3\gamma_3
\end{aligned}$$

In a like manner, equations which contain only terms of one order, *e.g.*, (21d), can be thought of as being more approximate than equations which contain terms of several orders, such as (21b).

These sets of equations were solved numerically for the case in which M_1 has a square wave shape, *i.e.*, for

$$\alpha_s = \frac{4|M_R|}{\pi s}, \qquad s = 1, 3, 5, \cdots. \tag{22a}$$

For such a case, the wave forms of H_1 and M_2 are also square, and the following relationships are true:

$$\beta_r = \frac{4|M'|}{\pi r}, \qquad r = 1, 3, 5, \cdots \tag{22b}$$

$$\gamma_t = \frac{-4|H_C|}{\pi t}, \qquad t = 1, 3, 5, \cdots. \tag{22c}$$

The values for $|M_R|$, $|M'|$, and $|H_c|$ were taken to be, respectively, 900 gauss, 740 gauss, and 280 oersteds. These are the values for the tape previously mentioned.

Since the equations are quadratic, it was found in solving these equations numerically that more than one solution could be found. In order to select the proper one, additional criteria were imposed which demanded that the correct solution be physically allowable. The criteria used are as follows:

1) The value of M and H at every point in the tape must occur in the second and fourth quadrants of an M-H plot.
2) $|a_k| \leq 2|M_R|$.
3) The potential energy of a bit must be lower after self-demagnetization has occurred than in the initial state; *i.e.*, $E_2 \leq E_1$.

[9] It can be shown that if a function $f(x)$ is defined in the interval

$$-\lambda/2 \leq x \leq \lambda/2 \quad \text{and} \quad \int_{-\lambda/2}^{\lambda/2} |f(x)|^2 dx$$

exists and if $f(x)$ is symmetric about the point $-\lambda/4$ in the interval $-\lambda/2 \leq x \leq 0$ and symmetric about the point $\lambda/4$ in the interval $0 \leq x \leq \lambda/2$, then $f(x)$ can be expressed in terms of a Fourier series containing only odd harmonic terms.

The first condition expresses the fact that in the state of self-demagnetization the direction of the field and the magnetization are 180° out of phase.

The second condition stems from the fact that the a_k's are Fourier coefficients and that the maximum absolute value which the magnetization can have is $|M_R|$. Consequently,

$$|a_n| = 2\left|\int_{-1/2}^{1/2} M \sin 2n\pi x dx\right| \leq 2|M_R|. \quad (23)$$

The third condition is based on the fact that self-demagnetization is an irreversible process. Using the definition for the potential energy of a permanent magnet given by Stratton,[10] it can be shown that the energy of a bit before self-demagnetization, E_1 is as follows:

$$E_1 = -K \sum_{s=1}^{m} \alpha_s^2 \quad (24a)$$

and after self-demagnetization, E_2 is as follows:

$$E_2 = -K \sum_{k=1}^{m} a_k^2[1 + A_k] \quad (24b)$$

where K is a positive constant dependent on the thickness and width of the tape and the wavelength. Consequently, 3) reduces to

$$\sum_{k=1}^{m} a_k^2[1 + A_k] \leq \sum_{s=1}^{m} \alpha_s^2. \quad (25)$$

The results of the solution obtained after applying this criterion are listed for various values of d/λ in Table II. For $m=3$, the solutions listed were obtained from (21a) and (21b); for $m=5$, equations corresponding to (21a), (21b) and (21d). These solutions do not satisfy all the remaining equations exactly, but only approximately. This is to be expected because of the varying degrees of approximation which the equations pass.

However, it is evident that the same solution occurs for successive values of m. This repetition of the same solution is taken as an indication that a solution exists for the infinite case, *i.e.*, $m=\infty$, and that the solutions obtained are approximations to the solution which would be obtained in that case.

Results obtained with the Kostyshyn method (Table III) compared with the ones given in Table II show general agreement. However, the model developed here shows a slightly greater effect. For example, in the Kostyshyn model at $d/\lambda=0.0250$, a_1 has changed from its initial value, α_1, by 8.8 per cent; α_3 by 22 per cent; and a_5 by 32.3 per cent; in the data presented here by 12 per cent; by 41 per cent; and by 36 per cent, respectively.

[10] J. A. Stratton, "Electromagnetic Theory," McGraw-Hill Book Company, Inc., New York, N. Y., pp. 129–130; 1941.

TABLE II
SUCCESSIVE APPROXIMATIONS FOR VARIOUS VALUES OF d/λ

	$m=1$	$m=3$		$m=5$		
d/λ	a_1	a_1	a_3	a_1	a_3	a_5
0.0050	1142	1128	362.6	1138	370.3	216.6
0.0125	1112	1108	344.7	1091	313.2	187.8
0.0250	1078	1072	316.6	1011	223.8	146.0
0.0500	1002	995.5	267.1	907.1	146.1	104.0
0.1250	787.3	762.5	161.5	746.4	131.5	79.2
0.2500	586.7	557.3	115.2	582.4	129.6	73.2

$\alpha_1=1145$ $\alpha_2=381.7$ $\alpha_3=299$

TABLE III
COMPUTED VALUES OF α_1, α_3, AND α_5 BY MEANS OF THE KOSTYSHYN MODEL

d/λ	a_1	a_3	a_5
0.0050	1114	361	209
0.0125	1082	331	186
0.0250	1044	297	155
0.0500	968	242	115
0.1250	777	161	85
0.2500	573	131	76

TABLE IV
SUCCESSIVE APPROXIMATIONS FOR VARIOUS VALUES OF d/λ

d/λ	α_1	α_3	α_5
0.0050	1008	269	115
0.0125	906	111	19
0.0250	700	87	13
0.0500	970	9	0
0.1250	450	0	0

No experimental data can be given to directly verify the result given in Table II since the initial magnetizations obtained experimentally are not square waves. However, the experimental data in Table IV does give general confirmation of the results in Table II, especially for the lower values of d/λ and the lower coefficients. This is to be expected since the nonsquareness of the initial magnetization would tend to decrease the higher coefficient more than the lower ones, and also to become more important at higher values of d/λ's. The value given in Tables II, III and IV all indicate that self-demagnetism become important for a_1 at about $d/\lambda=0.05$; for a_3, $d/\lambda=0.0125$; and a_5, $d/\lambda=0.005$. Table IV also indicates that there can be more important loss mechanism occurring than self-demagnetization.

The results obtained from the calculations performed indicate that there is a value of d/λ beyond which there will be no significant change in the a_k's, as can be seen by the behavior of a_3 and a_5.

CONCLUSION

As stated in the Introduction, the model proposed in this paper differs substantially from the model proposed by Kostyshyn. In the Kostyshyn model a boundary value problem is formed and is solved by means of a linearization and the use of a superposition principle. In the model proposed here, a boundary value approach is not taken. Instead, a method of undetermined coefficients, coupled with a phenomenological description of the self-demagnetization, is used which avoids the linearization and superposition which Kostyshyn employs in his solution.

For an initial square wave magnetization it was seen that the numerical values indicated by both models are very close. If the two models are composed for various trapezoidal-shaped initial magnetization, the results of a first-order approximation (*i.e.*, $m=1$) indicate that there is good correspondence between the two models for most values of d/λ. However, for higher values of d/λ, there might be as much as 20 or 30 per cent difference.

The results given in Table II indicate that self-demagnetization does not significantly change the value of a_n from the value of α_n for values of $d/n\lambda$ smaller than approximately 0.05. However, it is known that a change in shape of the initial magnetization from a square can substantially reduce the value of α_n, even for values of $d/\lambda<0.05$, as seen in Table IV. Here it can be seen that there can be a more important loss mechanism occurring in magnetic recording than self-demagnetization.

Even though the final equations developed in this paper were for symmetrical magnetization, this method could be used to treat asymmetrical magnetizations by retaining the even-numbered terms. The author also feels that this model could be applied to initial magnetization other than a series of ones.

As mentioned in the Introduction, the model employs the assumption that hysteresis loops can be applied to small elements of magnetic material. It is felt that the results obtained confirm this original assumption quite well.

In conclusion, the author feels that the results obtained indicate the feasibility of the model proposed in this paper.

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Some Techniques Toward Better Stereophonic Perspective*

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Summary—Improvements in stereophonic sound reproduction are identified with those qualities which cause the recorded performance to recall similar real performances in the minds of the listeners. This paper describes the results of research at CBS Laboratories toward improvements in recording of space perspective. Two experiments are described: 1) On the use of back-to-back limaçon microphones for reproducing correctly the direction of reverberation and other space sounds. 2) On the design and use of a device called the stereophonic spreader and shifter to spread a monophonic sound to cover any desired proportion of the stereophonic field, and then to position it anywhere in the field, within or outside the limits of placement of the loudspeaker. These devices are characterized as tools which may be used by the recording director to convey to the listener the desired artistic message.

Introduction

THE ART OF TRANSMISSION of directional sound perception may be said to have begun in 1881 when Ader placed a number of carbon-rod microphones in the footlights at the Grand Opera in Paris and connected them to several hundred pairs of Bell Telephones located at the Electrical Exhibition Hall. When listening with both ears to the telephone pairs, the sound took on a special character of relief and localization which a single telephone could not produce. This demonstration became among the most popular attractions at the Exhibition.[1] Crude as these experiments may appear today, they show clearly the unconscious power of the art forms which in our minds recreate past experiences. The character of sound, including intensity, pitch, timbre, angle of arrival and the rate of change of these qualities are a part of these experiences. In reviewing the advances of stereo sound, there is an unmistakable tendency toward improvement of those qualities which identify the recorded performance with a real performance in the minds of the listeners. These advances are taking place on all fronts: in sound reception, recording and reprodution. We touch lightly on a selected

* Received November 20, 1962: revised manuscript received June 17, 1963.
† CBS Laboratories, Stamford, Conn.

[1] H. A. Frederick, "The development of the microphone," *J. Acous. Soc. Am.*, vol. 3, pp. 8–9; July, 1931.

topic in the first area, describing some of CBS Laboratories research on how to pick up space perspective to achieve realistic stereophonic sound.

Recording of Space Perspective

The art of microphone placement for reception and recording of space perspective has undergone vast modifications since the time of Ader. Among the famous landmarks, the most popularly known was the Dummy Oscar at the Century of Progress Exposition in Chicago in 1933 with microphones in place of ears. Oscar provided excellent auditory realism of space perspective to observers wearing corresponding earphones. However, when spaced-apart loudspeakers were connected to the microphone channels, the feeling of space perspective disappeared. This is because, with loudspeakers, each ear received the sound from both channels, resulting in dilution of directional information. Obviously a greater "separation" between microphone channels was needed.

To whom the credit belongs for discovering that a sound source would appear to move unmistakably between two loudspeakers with gradual redistribution of signal intensity between the loudspeakers (panning), is not certain. With this scheme in mind, Blumlein[2] of Great Britain, proposed a directional microphones system which was capable of converting the angular direction of sound arrival into corresponding intensity differences at the loudspeaker channels. While Blumlein's scheme in theory appeared to provide an ideal solution to the reception of sound for two-track stereophony, in practice it has not proven to be entirely satisfactory. For one, it required fairly distant placement of the microphones from the performers, and unless the recording and reproducing studios were quite "dead," the definition, or "presence," was diminished. (Blumlein's work was intended mainly for motion picture recording and reproduction, where theatre acoustics may be closely controlled and the motion picture itself provides visual cues as to the direction of sound.) For improved definition in stereo recording, there developed gradually a tendency to use multiple microphone arrays placed near the performers, or groups of performers, with the separate channels recorded on multitrack magnetic tape. This procedure offers the further advantage of allowing the conductor or the artist to participate in the final editing session, during which the multiple channels are combined into two, thus making certain that the final master tape will meet the artist's approval.

But even this last scheme is not without travail. The closeness between the microphones and the performers often alters adversely the relationship between direct and reverberant sounds. Therefore, additional microphones for reverberation pickup must be provided during the original recording session, or a "reverberation chamber" is required during the final editing process. And here is the root of a problem for which some solutions are suggested in this paper.

Let us consider first what happens with a conventional echo chamber arrangement. This is shown in Fig. 1. The sound to be reverberated is introduced by means of a loudspeaker, and is picked up with a microphone placed in the chamber. Because of randomness of sound reflections, a person within the chamber would hear a reverberant sound evenly distributed in all directions. Emerging from the microphone line, however, is a monophonic signal. When the latter is connected to one of the loudspeakers, all the reverberation appears to emerge from the one loudspeaker. Or, if the microphone is connected to both loudspeakers, the reverberation appears to lie midway between the loudspeakers. No matter how such a reverberant signal is "panned" between the loudspeakers, it emerges as a monophonic sound.

This effect is noted not only with reverberation, but with other space effects. For example, a thunderclap is normally expected to reverberate through space. In a recent recording it was located precisely between the loudspeakers, which is quite unrealistic. Evidently this thunderbolt was recorded with a single microphone and placed on the center channel.

In order to distribute the reverberant sound, the scheme shown in Fig. 2 sometimes is adopted. Here, two microphones (and perhaps several sound sources, one for each channel) are employed, each being connected to one loudspeaker channel. It might be assumed that, since each microphone is subjected to a randomly directed sound wave, an over-all random effect will be noted. This, however, is not the case. Because the sounds arriving at each of the microphones are essentially incoherent, the two signals do not blend into a unified stereophonic image. Instead, semi-independent reverberant sounds are sensed to arrive from each loudspeaker.

Widely placed microphones produce especially unpleasant results when receiving space effects such as the sound of the sea, or of moving vehicles, etc. The resultant recording signal appears to jump from one loudspeaker to the other, with very little information in between. The problem, then, is how to add reverberant sound or to reproduce stereophonic space effects in an artistically appropriate manner.

One answer to this question is obtained with the aid of the "Stereophonic Law of Sines" recently formulated.[3] By this law, the location of a stereophonic virtual image as perceived by a centrally located observer, caused by in-phase (or 180 out-of-phase) signals, between (or outside of) the space encompassed by the loudspeakers is given by the equation:

$$\frac{\sin \theta_I}{\sin \theta_A} = \frac{E_l - E_r}{E_l + E_r} \qquad (1)$$

[2] Blumlein, Brit. Patent No. 394,325; December 14, 1931

[3] B. B. Bauer, "Phasor of analysis of some stereophonic phenomena," *J. Acoust. Soc. Am.*, vol. 33, pp. 1536–1539; November, 1961.

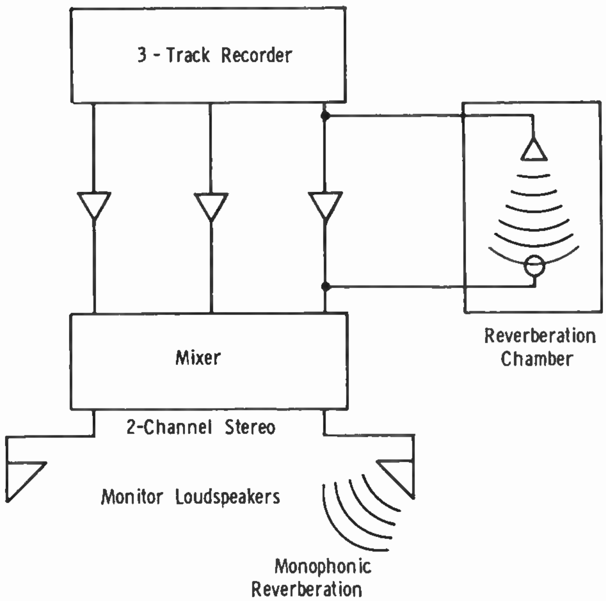

Fig. 1—A reverberation chamber with single microphone produces monophonic reverberation.

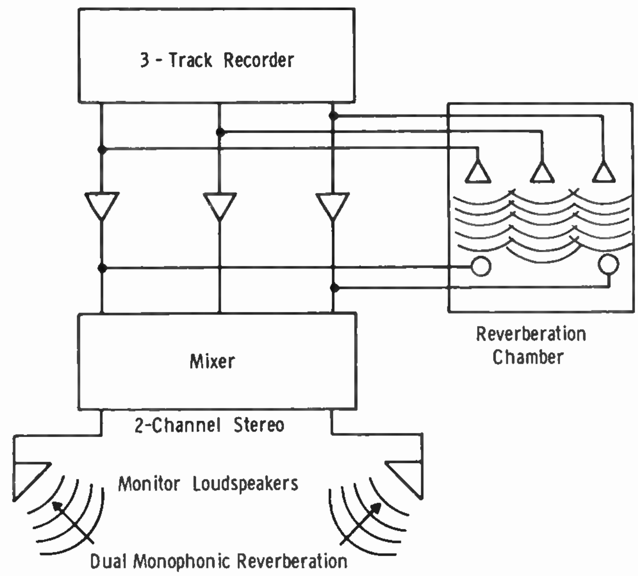

Fig. 2—A reverberation chamber with spaced-apart microphones produces dual-monophonic reverberation.

where θ_I is the position of the virtual image, θ_A is $\frac{1}{2}$ the angle subtended by the loudspeakers, E_l and E_r are the left and right channel signals.

Let us take two microphones exhibiting a lamaçon family pattern, placing them back-to-back, with the sensitive elements coincident or within an inch or so of each other, as shown in Fig. 3. Each microphone is connected to its respective left and right channel. The output voltage of the left microphone as a function of the angle of sound arrival θ, is given by the equation $K + (1-K) \sin\theta$, and for the right microphone it is given by the equation $K-(1-K) \sin\theta$, where K is a constant between 0 and 1 which determines the specific pattern. Substituting these values into (1) and simplifying, the following equation is obtained:

$$\frac{\sin\theta_I}{\sin\theta_A} = \frac{(1-K)\sin\theta}{K}. \tag{2}$$

It will be noted from (2) that the image position θ_I will be identical with the incident sound direction θ if $\sin\theta_A = K/(1-K)$. For the common loudspeaker placement of, say $\theta_A = 30°$, K is found to be $\frac{1}{3}$. With this choice of K the reverberant sounds will appear to the observer to be randomly distributed over a total angle of roughly 180°, and correctly proportioned as to the angle of incidence. By a similar reasoning, it may be shown that if the two microphones, placed back-to-back, exhibit a cardioid directional pattern, then $K=\frac{1}{2}$ and the random distribution of sound will cover a total angle $\theta_I = \theta_A$, thus extending from the limits of one loudspeaker to the other.

This back-to-back method of microphone placement is useful also for recording other space effects: the noise of a crowd, the applause of an audience, the roar of the sea.

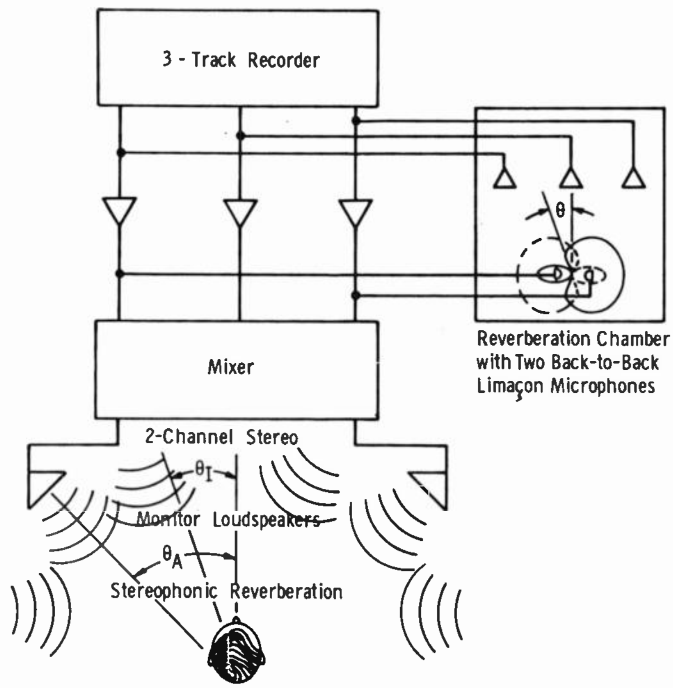

Fig. 3—Proximate back-to-back limaçon microphones (cardioid, super-cardioid, etc.) reproduce correctly stereophonic reverberation, space effects, etc.

Stereophonic Spreader and Shifter

Frequently the approach mentioned in the previous section cannot be employed, as when a single reverberation feed is available or when it is desired to "spread" the sound of a monophonic "take." This is accomplished by use of a sterophonic "spreader and shifter" which is a device recently developed at CBS Laboratories for randomizing and spreading the apparent direction of any sound to any desired degree and shifting it anywhere within the stereophonic field. Conveniently, a combined spreader-shifter (called "dimension control") may be connected in each channel leading to a final two-channel

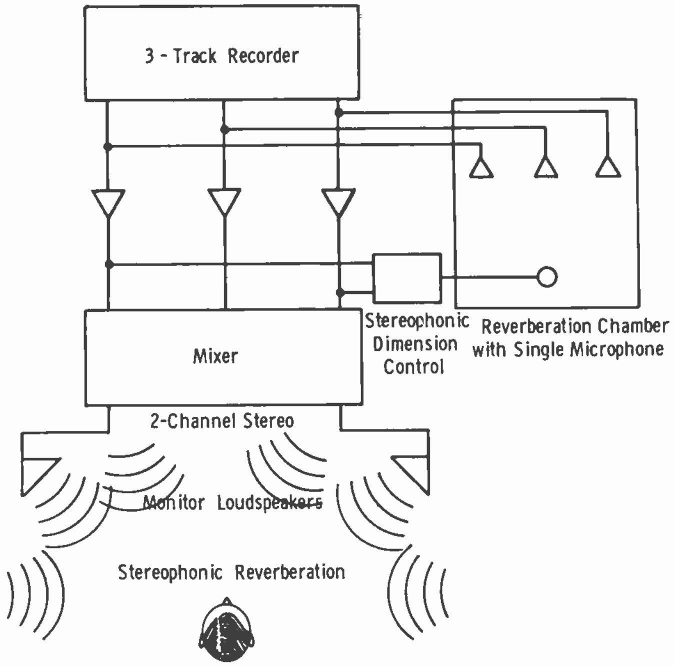

Fig. 4.—Production of stereophonic reverberation, space effects, etc., with stereophonic dimension control (spreader and shifter).

recorder and the monitoring loudspeakers or, as shown in Fig. 4, between the reverberation chamber and the final left and right channels. The spreader part splits the incoming signals into two separate channels, introducing continuously variable delays between them for any desired image width to be selected. The "shifter" portion allows the placement of this sound anywhere at, between or beyond the loudspeakers without substantially altering the amount of "spread" (if any) that might have been selected. Devices such as this one can be expected to play an increasingly important role in recording reverberation, spreading of space effects, increasing the width to a choir or instrumental ensemble, and otherwise providing a more artistically desired character to the recorded sound.

Stereophonic Spreader

The principle of the spreader-shifter is shown in Fig. 5. First we consider the spreader portion which is to the left of the vertical dash-line. The spreader consists of a network which splits an incoming signal E into two signals E_l and E_r which are equal in magnitude and differ in phase by an adjustable phase angle 2ϕ which is invariant with frequency. This is done conveniently by providing suitable delays $\phi_l(f)$ and $\phi_r(f)$ which differ by 2ϕ. For studying the effect of the spreader the signals E_l and E_r may be connected directly to two loudspeakers. We can write

$$E_l = E_0 \sin (\omega t + \phi) \tag{3}$$

$$E_r = E_0 \sin (\omega t - \phi) \,. \tag{4}$$

In developing this network I have hypothesized that, while equal in-phase signals applied to two loudspeakers for the central observer produce a sharp central image,

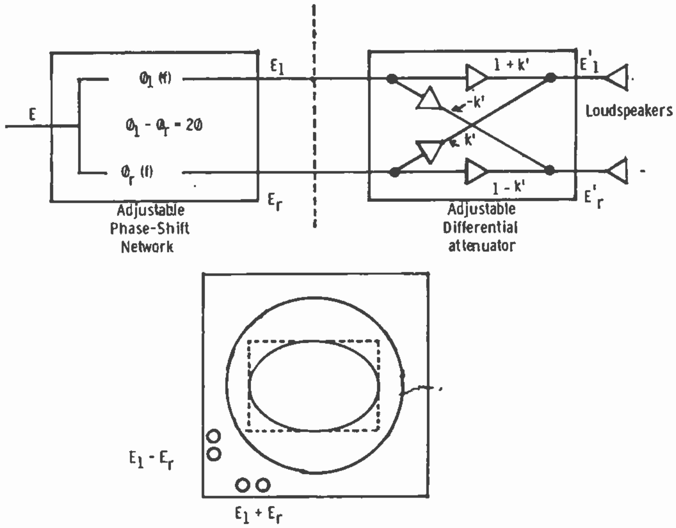

Fig. 5—Block schematic diagram of stereophonic dimension control (spreader and shifter).

and a constant delay tends to produce a shift of the image, a constant phase angle equivalent to a frequency-varying delay between the signals would produce a spread, fuzzy image, and indeed this has proven to be the case. As ϕ increases from 0 to 45°, making total phase angle between the signals 90°, the spread of the image also increases until it covers the whole space in between the loudspeakers; as the total phase angle is increased beyond 90° the image spreads beyond the confines of the loudspeakers until it covers the whole 180° frontal angle. These effects are perceived best in a relatively "dead" room, but to a lesser degree they are also noticed in a relatively reverberant space.

The effect of the spreader has been verified experimentally by all the observers who have listened to it. Its operation may be explained as follows: if one draws the sound pressure phasors at the left and right ears of the central observer, using the methods of Bauer,[3] the following differences are observed:

1) With in-phase equal signals applied to the loudspeakers the resulting pressures at the observer's ears are equal and in phase. This is presumed to have a connotation of sound with frontal direction.

With in-phase unequal signals applied to the loudspeakers the resulting pressures at the observer's ears are unequal and out-of-phase. The magnitude of pressure is greater at the ear nearest the loudspeaker with the more intense signal, and it also leads the pressure phasor at the opposite ear. This provides two reinforcing cues as to direction: magnitude and time delay corresponding to the phase.

2) With, say, 90° out-of-phase equal magnitude signals applied to the loudspeakers, the pressures at the ears of the observer are unequal and out-of-phase; however, the pressure magnitude is greater at the ear nearest the loudspeaker which has the 90° lagging signal, but it lags the pressure phasor at the opposite ear. Thus, the two directional cues tend to cancel each other: The observer is cognizant of the sound amplitude, but not of its

direction. The amount of confusion as to the direction appears to be related to the phase angle between the two loudspeaker signals. I am not entirely satisfied with this explanation, but offer it here as a guide for possible future research approaches.

It is interesting to place the resulting signals E_l and E_r on the screen of an oscilloscope. To cause the image to portray the tip motion of a stereophonic cutter or pickup, the sum signal E_l+E_r is applied to the horizontal plates and the difference signal E_l-E_r is applied to the vertical plates.[4] Say the sensitivity constant of oscilloscope beam deflection is k cm/volt. Then in terms of x and y deflections the trace produced by sinusoidal signals may be formulated as follows

$$x = k(E_l + E_r) = 2kE_0 \sin \omega t \cos \phi \tag{5}$$

$$y = k(E_l - E_r) = 2kE_0 \cos \omega t \sin \phi. \tag{6}$$

Eqs. (5) and (6) express an ellipse in parametric terms, with a horizontal axis equal to $4KE_0 \cos \phi$ and a vertical axis equal to $4KE_0 \sin \phi$. With ϕ = zero, the two signals are in phase and the ellipse reduces to a horizontal straight line. With $\phi=45°$ (corresponding to a 90° phase shift between E_l and E_r) both axes are equal and the resultant figure is a circle. The ellipse may be inscribed in a rectangle, with sides equal to the major and minor axes. A diagonal of this rectangle will portray the trace of two in-phase signals of unequal magnitude applied to the two loudspeakers. Such signals generate a virtual stereophonic image displaced from the center by an angle θ_I defined by (1). I conjectured that the spread of the stereophonic image from the spreader will just fill the confines of an angle $\pm\theta_I$ corresponding to the diagonals of the rectangle in which the ellipse is inscribed. In other words

$$\pm \sin \theta_I / \sin \theta_A = 4kE_0 \sin \phi / 4kE_0 \cos \phi = \tan \phi. \tag{7}$$

In practice, the conjecture appears to be well satisfied. With $\phi=0$, *i.e.*, in-phase signals, $\theta_I=0$ and the image is, of course, centered and sharply defined. With $\phi=45°$, the total phase angle between the signals is 90°; $\tan \phi=1$, and as mentioned before $\theta_I=\pm\theta_A$ with the diffused image covering the whole space in between the loudspeakers. With the condition where $\tan \phi \sin \theta_A=1$, $\pm\sin\theta_I=\pm 1$, $\theta_I=\pm 90°$ and the diffused image covers a 180° space. With each loudspeaker at 30°, for example, $\sin \theta_A=0.5$ and $\phi=\text{arc} \tan 2=63.5°$. The total phase angle between the signals is $2\phi=127°$. The experimental spreader built at CBS Laboratories provides an adjustment capability for 2ϕ from 0 to 130° and it has been used to demonstrate the validity of (7). Many experienced listeners expressed a preference for the spread sound when listening to monophonic records.

Stereophonic Shifter

Once a stereophonic image is obtained, as by the use of a spreader, or in any other way, it may be desired to place it anywhere within the confines of a stereophonic field without altering the relative position of its components. This is done by means of an adjustable differential attenuator at the right-hand side of the dash-line in Fig. 5 called the shifter. The signals E_l and E_r are modified by the attenuator so that the relative output voltages at the left and right loudspeakers become E_l' and E_r', as follows:

$$E_l' = (1 + k')E_l + k'E_r \tag{8}$$

and

$$E_r' = -k'E_l + (1 - k')E_r \tag{9}$$

where k' is conveniently adjustable from -1 to $+1$.

With $k'=0$, $E_l'=E_l$ and $E_r'=E_r$ and there is no shift. In other words, the signals at the loudspeakers are the same as if the shifter were not present. As k' is adjusted in the positive or negative direction, the sound field shifts toward the left or right, respectively. We investigate the position of the stereophonic image when $k\neq 0$.

First we simplify (1) by writing $E_l=k_1E$, and $E_r=(1-k_1)E$. The position of the image θ_I without the shifter, then, is given by

$$\begin{aligned}\sin \theta_I/\sin \theta_A &= (k_1 - (1 - k_1))/(k_1 + (1 - k_1)) \\ &= 2k_1 - 1.\end{aligned} \tag{10}$$

As a second step, we substitute into (1) the respective signals from the shifter, as given by (8) and (9). Again, writing $E_l=k_1E$ and $E_r=(1-k_1)E$

$$\sin \theta_I/\sin \theta_A = 2k_1 + 2k' - 1. \tag{11}$$

Comparing (10) and (11), it is seen that the shifter adds a change in position corresponding to $2k'$ to whatever position had existed for various stereophonic sounds prior to the introduction of the shifter. Thus, with the spreader and the shifter it becomes possible to take a monophonic signal of any type, spread it into a stereophonic diffused signal covering any desired angle in space, and then, move the spread portion to any desired position in the stereophonic field without altering its dimensional perspective.

Conclusion

The described methods for microphone pickup of space perspective and for spreading and shifting a signal throughout the stereophonic field are not in themselves the answer to the problem of "identifying the recorded performance with the real performance in the mind of the listeners." Some workers in the field like them and some do not. The engineer must respect the opinion of the artist and the recording director as to what constitutes the optimum portrayal of the artistic message which the latter wishes to convey to the listener. These methods illustrate, however, how psychoacoustics and physical science may combine for continued improvements in the art of sound recording and reproduction.

[4] B. B. Bauer and G. W. Sioles, "Stereophonic patterns," *J. Audio Engrg. Soc.*, vol. 8, pp. 126–129; April, 1960.

Experiments with Electron Scanning for Magnetic Recording and Playback of Video*

MARVIN CAMRAS†, FELLOW, IEEE

Summary—Present-day video tape uses high-speed mechanical scanning, with rapid wear of tape and heads. Electron-beam scanning is proposed to eliminate mechanical problems and to allow the use of low cost tape. Development work has been conducted on a recording tube using a high-density sheet beam to energize a simplified 500-element magnetic head. For playback a tube was built with a line of fine high-permeability wires sealed into the envelope in the beam path.

EARLY TELEVISION systems depended on mechanical scanners such as the Nipkow disk to convert a picture into a video signal and vice versa. Electronic scanning became perfected before television was commercialized. Whether mechanical scanning could have had a similar measure of success in the absence of CRTs is a subject for interesting debate. One can point out that where electronic means were not available, mechanical devices such as piston-driven automobiles, for example, have become popular; even though at the outset one might have argued that they were too complicated, noisy and clumsy, and, therefore, would have to wait for jet or ion propulsion.

In the late 1940's when the problem of recording video was encountered, one should have looked at the history of television, itself, and noted that mechanical scanning had been tried for a half-century, but television didn't become practical until electronic methods were developed. Therefore, experience, as well as common sense, indicated that at this advanced state of technology a modern approach to recording should be electronic.

As proved by later events, experience and common sense are not always accurate. Ten years afterward video recording was in extensive use, but the method was high-speed mechanical scanning. In spite of its success, everyone in the industry has felt that there ought to be a more refined way. In the long run, mechanical scanning may yet give way to the "common sense" approach.

Over-all Requirements

Regardless of what our video recording black box contains, it must accept a 4.5-Mc signal of present TV standards during recording and must play back a reasonable facsimile of the original.

The megabits of information may be arranged on the tape in almost countless ways, but there are advantages in choosing a format where horizontal scans on the tape correspond to lines of the picture, as shown in Fig. 1. In this case the magnetic pattern on the tape is an image which can be made visible by dusting with fine magnetic powder, and which can be edited like motion picture film. Registration requirements are easier than with other formats since errors in alignment will displace the reproduced picture as a whole, whereas, a jumble results if successive lines have unrelated information.

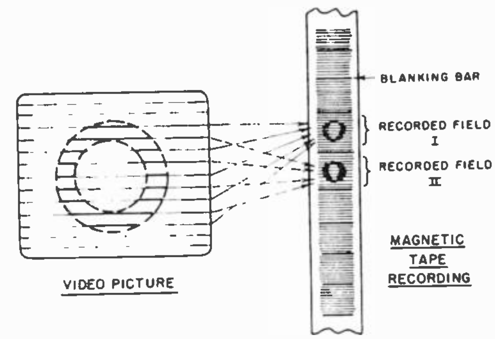

Fig. 1—Relation of tape recording to the video picture.

Recording Head

Along each horizontal line, one should be able to resolve about 300 to 500 bits. This calls for an array of heads provided with means for lateral scanning. If they were of conventional construction, these would be prohibitive in cost, reliability, and space requirements. A basically simple and compact multigap head, as in Fig. 2, was devised. The core is a thin sheet of mumetal with teeth machined in it so that it resembles a miniature saw blade. The core is held in the slot of a copper head casing having an insulated top surface. The coils are single conductors laid in each groove. One end of each conductor is connected to the lower part of the head casing for a common return circuit, while the other end is energized, as will be explained later. For the experimental unit, a pitch of eight mils (0.008 in) was chosen, allowing 125 heads per inch, or somewhat under 250 heads on a tape two inches wide.

The gaps thus formed are four mils wide and spaced four mils apart. A current of one ampere through the single turn produces a recording field of approximately

$$H = \frac{0.4\pi NI}{l} = \frac{0.4\pi}{0.004 \times 2.54} = 124 \text{ oersteds.}$$

This signal is considered to give nearly the full linear range of recording on a biased tape. If the gap size is reduced, as by choosing a finer pitch, the current for a given field goes down proportionately. The gaps can also

* Received March 29, 1963.
† Armour Research Foundation, Chicago, Ill.

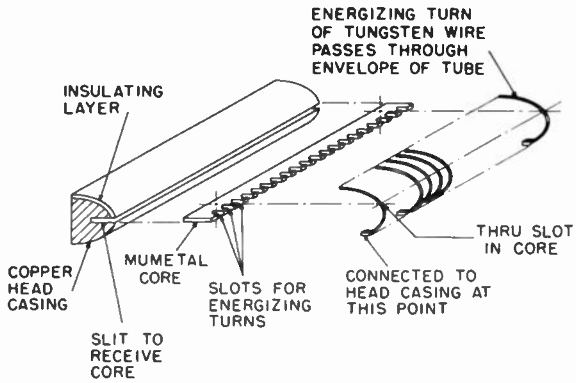

Fig. 2—Video recording head details.

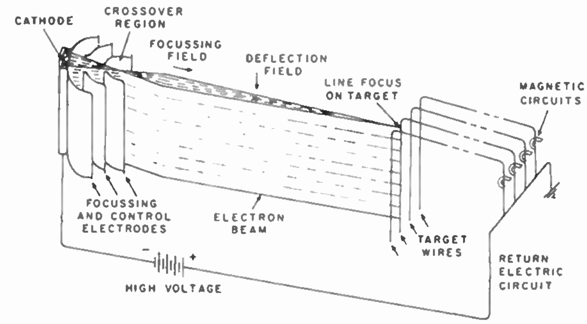

Fig. 3—Electron-beam system of recording tube.

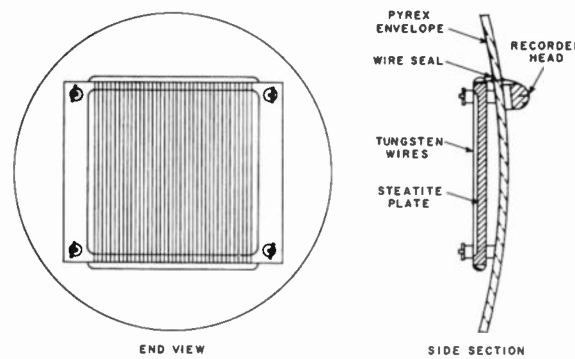

Fig. 4—Target assembly for recording tape.

be reduced by "mushrooming" the top edge of the core.

Although a current of one ampere seems high, each head operates only 1/250th of the time, so its average current and power are small. Recording will still take place at lower signal currents but at a less favorable SNR. If full range recording gives a SNR of 40 db, a reduction in current of 30 to 1 (to 0.033 a) yields a recording about 10 db above the noise level, which is tolerable for experimental purposes, even though not of highest fidelity.

Electronic Scanner

For recording, the scanner is an electron-beam tube which connects with each of the heads in turn until a horizontal line of video is recorded. The beam is then blanked out and returned to the first head to begin the next line of sweep. Each head magnetizes the tape in accordance with the video signal at the instant that the head is active.

It is evident that conventional CRTs with beam currents of microamperes are inadequate. Since the recording tube sweeps in the horizontal direction only, we can increase the current greatly by broadening the electron beam in the vertical direction, so that its cross section is a line instead of a spot, as shown in Fig. 3. This calls for an electron gun of cylindrical symmetry, rather than of the usual circular symmetry.

The greater the vertical dimension of the beam, the smaller will be the beam current density, and the easier it will be to focus the beam to a fine line. On the other hand, a beam of considerable vertical height requires accurate electrodes and magnetic fields to keep it straight and aligned with the target. In the experimental tubes a two-inch vertical beam height was chosen. The active horizontal portion of the target was two inches wide also, the same as the width of the tape and of the head. The target area was then two inches square, and the magnetic head could be mounted directly on the face of the tube.

Fig. 4 shows the target assembly in more detail. A tungsten wire grid was stretched across a steatite plate. Tungsten was selected because it is nonmagnetic, because it can withstand high temperatures, and because its coefficient of expansion allows sealing into Pyrex glass. The bottom ends of the wires are insulated from each other. The top ends pass through the tube face, through the recording head core slots, and are electrically connected to the lower head support which acts as a bus bar.

Experiments

Using an elongated cathode from a 715C radar pulse tube which was capable of supplying about one ampere of pulse current, a high-current electron gun of the configuration shown in Fig. 3 was built. The cathode sleeve was reshaped to have a concave face and mounted with the curved electrode structure formed from molybdenum plates. The electric fields were such that the beam would converge at a crossover region. The diverging tendency beyond this region was counteracted by a magnetic field, which could be adjusted to bring the beam to a line focus on the target wires.

The recording tube was energized, as shown in Fig. 5. The higher the maximum voltage, the easier it was to obtain a high-density beam in fine line focus. Higher voltage increased the energy dissipation and also affected secondary emission. Focusing the beam was aided by a longitudinal magnetic field. Horizontal sweep coils and circuits were conventional.

The electron gun was tested with a face plate having a set of spaced individual wires, as shown in the left lower portion of Fig. 6. A metal flag coated with willemite was welded to one of the wires. When the beam was directed to strike this flag, the fluorescence gave an indication of the location and focus of the beam. It was desirable to use the same electron gun with various

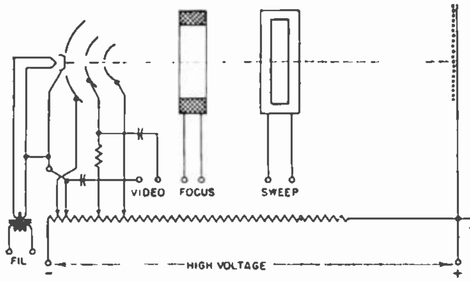

Fig. 5.—Circuit for the recording tube.

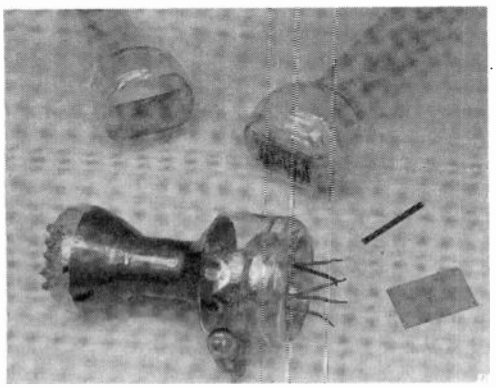

Fig. 6—Experimental recording tubes.

targets and yet allow the tube to be sealed off from the vacuum pump. This was accomplished by having the "getters" in an auxiliary tube attached to the main envelope, as shown at the bottom of Fig. 6. A new "getter" was used every time the main tube was opened.

With a beam voltage of 850 volts, it was possible to obtain a steady current of 35 ma at a selected target wire, and the beam could be focused to a line that was a few mils wide. The gun design was, therefore, considered adequate for its purpose.

Attention was now turned to the fine multiple-wire target and head assembly. The main difficulty here was in bringing the 250 fine wires through a glass envelope with a vacuum-tight seal around each one. It was not feasible to use open-flame techniques, which were successful with larger sizes of tungsten wire. At the high temperatures required to melt Pyrex glass, a green powder, apparently tungsten oxide, was eroded from tungsten wires and fused with the glass. When the wires were very fine, as in our case, the erosion wore entirely through the metal. An electric oven was tried instead of the flame, but the results were similar, showing that the cause was temperature, rather than the flame.

A nonoxidizing atmosphere was successful in eliminating the erosion. Of the atmospheres tried, helium gave the best results. Experimental seals into Pyrex envelopes of Fig. 6 are shown prior to cutting the wires at the bottom and laying them into the grooves of the recording head.

The Playback Scanner

Requirements for electronic scanning in playback of a recording such as in Fig. 1 are much less severe since high beam currents are not involved. The electron gun, focusing, and sweep elements are similar to those in a television receiver, or an oscilloscope.

The main problem is to couple the recorded magnetic field to the electron beam so as to modulate the latter. The beam modulation is then translated into the desired video signal. Magnetic coupling between the recording and the beam must be close; otherwise, sensitivity and resolution are lost. It is most convenient to run the tape outside of the vacuum tube, although, with added complications, it could be run in a vacuum chamber. One way of coupling an external record is to run it past a very thin vacuum-tight window, adjacent to the beam on the other side. A more rugged construction is to utilize high-permeability ferromagnetic members to bring the field of the tape through the tube envelope.

One may operate on the direct beam or on a reflected beam. Fig. 7 shows the design of a direct-beam playback tube. The electron beam passes through a set of magnetically permeable wires on its way to a split anode. Depending upon direction of the magnetic field from the record between a particular pair of wires, the beam is deflected either up or down, thereby increasing or decreasing the current to the upper anode and resulting in a video signal into the amplifier as the beam is swept past the magnetic comb.

A reflected-beam tube is shown in Fig. 8. Here, the beam passes through a split anode towards a comb of magnetic deflecting wires in the face of the tube. The tube face and wires are electrically nearly at cathode potential, so that the forward electron velocity is reduced to zero as they approach the face. The electrons reverse direction in the vicinity of the wires and are picked up by the split anodes. A magnetic field between any pair of wires will deflect the return beam as it sweeps past those wires, causing a momentary increase in current at one of the split anodes.

A number of experimental playback tubes was built, the most successful design being the reflected-beam type. Preliminary tests were made on a tube such as the one in Fig. 9, with a single set of high-permeability magnetic wires passing through the tube envelope. The electron beam was deflected so that it passed between these wires and then was attracted to the target plate which it struck at grazing incidence. Against the external stubs of the magnetic wires, a pair of mumetal polepieces were placed, which defined a short gap similar to that of a playback head. A prerecorded tape was run past the gap, and the recording could be heard distinctly as modulation of the target current.

After favorable results had been obtained with preliminary models such as the above, the investigation was directed towards construction of a playback tube with a face plate having 250 four-mil wires in a straight line. It is fortunate that an alloy of high magnetic permeability, and having the same expansion coefficient as certain glasses was available. This material is 4750 alloy, having an analysis of approximately 47 per cent of nickel and 53 per cent of iron. Its initial permeability is about

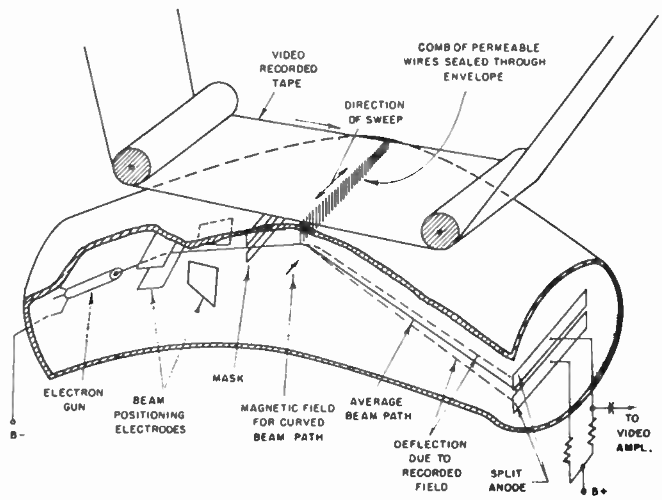

Fig. 7—Direct-beam playback tube.

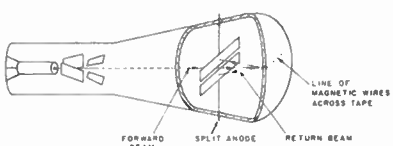

Fig. 8—Reflected-beam tube.

5000 to 10,000. The wires sealed nicely into 60-mil soft glass plates in a protective atmosphere of helium. The glass face was in turn sealed into the electron-beam tube, as shown in Fig. 8. It was possible to seal off the tube and to maintain a hard vacuum, showing that the multitude of individual wires were all vacuum tight.

The experimental drive for the electron-scanning system is shown in Fig. 10. The magnetic tape is two inches wide and runs at fifteen inches per second. The playback tube is mounted inside a mumetal shield. A felt pressure pad on the back side of the tape maintains it in contact with the row of magnetic wires in the tube face.

Discussion of Results

This experimental study of scanning for video recording indicates that the electronic method is feasible; it also indicates some of the refinements that are necessary before it can become "commercial."

To improve the dynamic range in the recording system, it is desirable to increase the recording current available from the scanner, or to decrease the current required for full range recording. The current can be increased by use of higher voltages, limited by the target dissipation which could be improved considerably by a heat sink. Increased current can also be obtained by making the scanning tube larger, using the same head size. Before doing this, it would be profitable to explore methods of using lower current. One approach is to increase the tape sensitivity, but at the expense of other properties. The head can be made more current sensitive by decreasing the gap size or by multiple turns, but again at the expense of complexity.

In the playback tubes an increase in sensitivity would

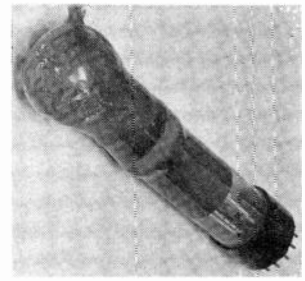

Fig. 9—Electron-beam tube for playback of single-channel magnetic recording.

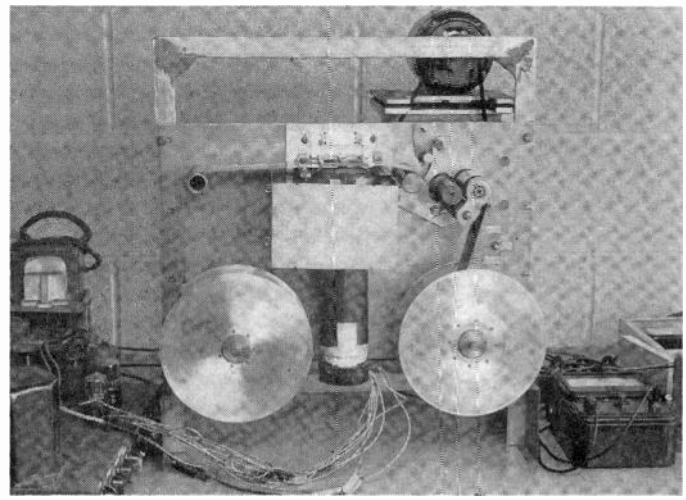

Fig. 10—Experimental drive for electronic tape scanner.

be welcome, particularly if finer wires and narrower tapes are to be used. The most difficult problems from the constructional standpoint are the special electronic tubes which are the heart of the system. And in these tubes the multiple wire seals are the most difficult and the most important.

Conclusion

To be competitive with the highly refined mechanical video recording standards in broadcasting at present, the electronic system should be equivalent in performance. There are also many noncompetitive uses where low cost and simplicity are prime considerations.

For nonbroadcast uses, a tape less than two inches in width and running at a slower speed than fifteen inches per second is desirable. Corresponding to 16-mm motion picture film, we might use half-inch tape at $7\frac{1}{2}$ ips., and corresponding to 8-mm film, the tape might be quarter-inch at $3\frac{3}{4}$ ips. Magnetic tape itself has adequate resolution size for size to equal or exceed photographic film; the problems are in the associated equipment.

Although the difficulties in electronically scanned magnetic recording are formidable, there is promise of video recorders which would be comparable in price and in complexity with present-day television receivers. If history is a guide, it seems inevitable that electronic means will eventually do the job better than high-speed mechanical scanners.

Correspondence

The Wear of Magnetic Recording Tape and Solubility of the Binder*

The ability of magnetic recording tape to perform satisfactorily after repeated use is a characteristic of critical importance in computer service. Wear tests of tapes are time consuming and have not always shown good agreement in the rank ordering of tape between different transport mechanisms and different criteria of end of life. The ability to withstand repeated use is governed to a certain extent by the composition of the binder and its adhesion to the plastic backing. Since the solubility of the binder in various solvents depends on its composition, experiments were run to see how well solubility could be correlated with wear. This communication is to bring attention to this work which is reported in more detail in other reports.[1,2]

The experimental procedure was to use about an inch length of tape in about 10 ml of solvent. Six solvents were used: acetone, ethyl alcohol, benzene, toluene, carbon tetrachloride and trichloroethylene ($C\,cl_2{:}CH\,cl$). The tests were conducted at room temperature and 4 solvent classifications used based on the ease of binder dissolution.[2] The tapes used (85 in number) were obtained from three other government agencies. Specimens from the same reels had been subjected to wear tests based on dropout studies. The results obtained from these wear studies were classified into four groups depending on their degree of wearability, as measured by the numbers of dropouts.

A comparison was made between the two criteria of classification.[2] To this end a two-way table was constructed consisting of sixteen cells, each cell representing a combination of a solubility rating with a wear rating. Sixteen of the twenty-eight experimental points fell in cells occupying the principal diagonal of the table. All but two of the remaining points fell in cells that bordered on the principal diagonal.

Using this approach, more than 100 used tapes of various degrees of wear were tested. As was to be expected, this solvent-resistance test does not differentiate between degrees of wear. The tapes fell into the same solvent-resistance classifications as the new tapes of the same type. This test is restricted to differentiating between new tapes as to possible future wear properties. Though this is by no means a conclusive test the results seem to indicate that this rapid and simple procedure, with further development, might become useful as a tool in quality control.

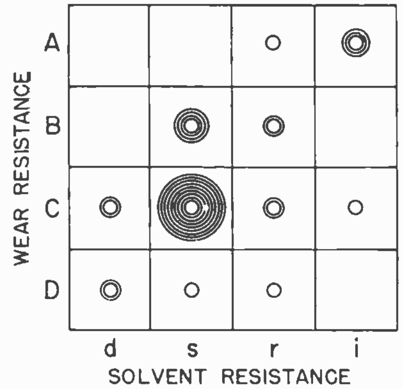

Fig. 1—Cross plot of wear resistance vs solvent resistance. *A*, *B*, *C* and *D* are classifications as to wear on recording equipment. *A* represents those tapes with the least number of dropouts for a given number of passes and *D* represents those tapes with the most dropouts for the same number of passes. The *i*, *r*, *s* and *d* classifications refer to binder solubility as follows: *i*, insoluble; *r*, dissolves only under the brush; *s*, dissolves on stirring; *d*, dissolves rapidly.

Work is under way at present in other laboratories to set up a carefully controlled study of tapes used on 13 different recorders, together with the corresponding solvent tests.

Florence Nesh
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* Received, May 7, 1963. Additional material received May 14, 1963, and May 29, 1963. The work for this paper was performed while the author was with the National Bureau of Standards, Washington, D. C.

[1] F. Nesh and R. F. Brown, Jr., "A study of the chemical and physical properties of magnetic recording tape," IRE Trans. on Audio, vol. AU-11, pp. 70–71; May-June, 1962.

[2] F. Nesh and R. F. Brown, Jr., "Magnetic Recording Standards," National Bureau of Standards, Washington, D. C., ASTIA Rept. No. 277830; July, 1962.

Comment on "A Network Transfer Theorem"*

Mr. Montgomery[1] sets out a Theorem which I myself published, with an almost identical proof.[2]

I there pointed out the great practical advantage of the Theorem in allowing current ratios to be measured, without introducing the current-meters which would upset circuit conditions, by observing a voltage-ratio under reversed transmission conditions; this was not noted by Mr. Montgomery.

Inquirers will find that, by some accident, my contribution was not listed in the Index of the *Wireless Engineer;* my theorem has in consequence never been referred to in the standard texts. It follows that I cannot blame Dr. Hurtig for introducing it in 1956 as a novelty.

The derivation occurred, almost by accident, as far back as 1929–30 when I had observed that the open

* Received June 12, 1963; revised manuscript received June 19, 1963.

[1] G. F. Montgomery "A network transfer theorem," IRE Trans. on Audio (*Correspondence*), vol. AU-10, p. 88; May–June, 1962.

[2] E. Ramsay Wigan, *Wireless Engineer*, vol. 26, p. 409; 1945.

circuit voltage-ratio measured between the two ports of a network A and B could be expressed in terms of three impedances:

ZA, measured at A with B closed;
ZB, measured with B with A closed;
and ZAB, measured at A with B open,
or ZBA, measured at B with A open.

Then, writing $_Ae_R$ = ratio of open circuit positive definite at B due to a generator EMF at A,

$$_Ae_B = \sqrt{\frac{ZB}{ZA}\left(1 - \frac{ZB}{ZBA}\right)}$$

$$\text{or} = \sqrt{\frac{ZB}{ZA}\left(1 - \frac{ZA}{ZAB}\right)}.$$

I had also derived a similar sort of equation in terms of input currents and output short-circuit currents:

$$_Ai_B = \sqrt{\frac{ZA}{ZB}\left(1 - \frac{ZA}{ZAB}\right)} \text{ or etc.} \cdots$$

On glancing over these equations it was observed that, by reversing the suffices,

$$_Ae_B = {}_Bi_A$$

which is the formal statement of my Theorem.

Later, of course, a simpler method of deduction was formulated.

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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 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 the Acoustical Society of America, and a member of SMPTE, AAAS, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. Offices held include PTGA Chairman and Editor of these Transactions and President of ITT Chapter Sigma Xi. He received the John Scott Medal in 1955, and the IRE PGA Achievement Award in 1958.

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He served in the U. S. Marine Corps from 1952 to 1954. He worked for the Phillips Petroleum Company, Bartlesville, Okla., during the summers of 1960 and 1961, where he designed a substantial portion of a data collection system and co-designed a sequential analog computer. In the summer of 1963 he worked for the California Research Corporation, La Habra, Calif., where he tested and evaluated magnetic tape used in seismic recording. He is presently working toward the Ph.D. degree at the University of Oklahoma.

Mr. Hinrichs is a member of Tau Beta Pi, Sigma Xi, Pi Mu Epsilon and Eta Kappa Nu.

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