IRE Transactions on AUDIO

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CONTRIBUTIONS

CORRESPONDENCE

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Professional Group on Audio

World Radio History

IRE PROFESSIONAL GROUP ON AUDIO

The Professional Group on Audio is an organization, within the framework of the IRE, of members with principal professional interest in Audio Technology. All members of the IRE are eligible for membership in the Group and will receive all Group publications upon payment of an annual fee of $2.00.

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World Radio History

The Editor's Corner . . .

THE OLDEN DAYS

Do you remember when:

The perfectionist would wire his set with tinned bus-bars, made of No. 14 solid copper. All wires crossed at right angles to prevent inductive coupling. Spaghetti tubing was used at the crossovers for insulation.

Everything had to be "low loss." There were low loss condensers and low loss coils. Bakelite was the wonder material for low loss panels and low loss wired decks. One manufacturer even advertised a low loss resistor.

Variometers were the last word in tuned circuits.

Experts talked about logarithmic decrement, instead of Q.

The higher the resistance of a pair of earphones, the better its quality was supposed to be, since the coils had more turns. However, we were warned to watch out for cut-price phones which were wound with resistance wire so that they would test high-resistance.

Baldwin earphones were considered the best. These were really a pair of loudspeakers with a headband to hold them apart.

Reflex circuits saved money by making one tube do the work of two or three.

To express the ultimate in audio perfection we said "broadcast-quality" instead of "high-fidelity."

Expensive microphones for broadcast stations were the double-button type with a stretched gold-sputtered duraluminum diaphragm and polished carbon granules.

NBC condenser microphones were cubic boxes with built-in preamplifiers.

Turner crystal microphones sold for $13.23 and were the poor man's answer to "broadcast quality."

Broadcast station announcements were introduced by Rangertone chimes - - - - - - - - - - "bong-bing-bong."

Electronic devices had "A" batteries for filaments, "B" batteries for plate supply, and "C" batteries for bias.

You were never really initiated into radio until you had connected the B batteries across the filaments and burned out a whole set of tubes.

MARVIN CAMRAS, *Editor*

World Radio History

PGA News

NEW PGA OFFICERS FOR 1962

Results of the recent election are as follows:

Robert W. Benson, Chairman of the Administrative Committee 1962–1963

Frank A. Comerci, Vice Chairman of Administrative Committee 1962–1963

Edward E. David, Donald F. Eldridge, and **James F. Novak,** Members of the Administrative Committee 1962–1965.

Michel Copel has been appointed as Secretary 1962–1963.

Biographies of the new officers will appear in a forthcoming issue.

PGA AWARDS

The following awards have been announced for 1961:

PGA Achievement Award—J. Ross MacDonald

PGA Senior Award—W. H. Beaubian and H. B. Moore

PGA Award—William H. Pierce

Further details will be given in a future issue.

CHAPTER NEWS

Chicago

"Transducers for the Measurement of Sound, Vibration, and Strain," was presented by George W. Kamperman on Tuesday, January 16, 1962, at a meeting held in the new Chemistry Research Building of Armour Research Foundation. A summary of the talk appeared in *Scanfax:*

> Many types of transducers are available for the measurement of physical phenomena. The characteristics of present-day electromechanical transducers used for dynamic measurements will be covered, with particular emphasis on their proper application and their limitations.

George W. Kamperman received his B.S. from Alma College, Michigan, in 1951, and has pursued graduate studies in acoustics at the Massachusetts Institute of Technology. He was associated with the acoustics laboratory at the General Motors proving ground from 1948 to 1951. Since 1951 he has been with Bolt Beranek & Newman Inc., where he has been responsible for the development of new equipment and procedures for sound and vibration measurements. He is now Senior Consultant in their Chicago office.

The March 7 meeting featured a discussion of:

> *High-fidelity—Where Do We Go from Here?*—A panel by Karl Kramer, Jensen Manufacturing Co. (Moderator); Dick Schory, Ludwig Drum Co.; A. B. Clapper, Universal Recording Corp.; George Lang, WGN; and Ralph P. Glover, Jensen Manufacturing Co.
>
> The panel discussed the status of high fidelity in an attempt to clarify the objectives of high fidelity systems, including the source material. The panelists attempted to answer such questions as: What is good high fidelity? How well is high fidelity achieved? Where do we go from here?

Karl Kramer, Manager of Technical Services of Jensen, is a graduate of Ohio State University, and has been with Jensen since 1935. He is a registered professional engineer in Illinois, and is a member of AIP, ASA, REC of Chicago, CAAG, and PGA, He is a Past-Chairman of the Chicago Section.

Dick Schory, recording artist, is a graduate in music of Northwestern, and has had several best seller albums, as well as pioneering the "stereo action series" of RCA. He is president of the Chicago chapter of NARAS and 1960 "Grammy" award nominee for best arranger. He conducts and arranges for RCA in Chicago and is currently with the Ludwig Drum Co.

A. B. Clapper is President of Universal Recording Corp. He attended Valparaiso and Drexel Institute of Technology. He is central vice president of the AES, a member of the national board of governors and Chicago chapter treasurer of NARAS. He received the 1961 best sound engineer "Emmy" from the Chicago chapter of NARTVS.

Ralph Grover is Vice President of Jensen. He is a graduate of the University of Cincinnati, and has been an engineer with Crosley Radio Corp., chief engineer of Shure Brothers, manager of Voltage Regulator Division, Webster Products, and a product consultant in acoustics. He is a member of the ASA.

(From *Scanfax*, March, 1962.)

Cleveland, Ohio

"Information Density of Magnetic Recording and Other Systems," was the subject of a talk by Marvin Camras, on April 12, at a joint meeting of the Cleveland and Akron Sections.

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Announcements

New Journal

Sound, its uses and control, is a new magazine published bimonthly by the Acoustical Society of America. It is devoted to the popular presentation of practical information on the uses and control of sound, including Noise Control, Shock and Vibration, Architectural Acoustics, Electroacoustics, Underwater Sound, Sonics and Ultrasonics, Musical Acoustics, Hearing and Speech, Bioacoustics, Psychoacoustics, Geoacoustics, Book and Patent Reviews, and New Products.

Subscription rate is $8.00 per year in U.S.A., Canada, and Mexico ($5.00 to members of the Acoustical Society of America). Foreign mailing is $2.00 extra. Application for subscription should be made to the American Institute of Physics, 335 East 45 Street, New York 17, N. Y.

REPORT OF COMMITTEE ON CHAPTERS AND MEMBERSHIP

The Committee on Chapters and Membership continued the program it has previously conducted. During the last six months, it has endeavored to contact all of the active chapters to determine their plans for the coming season. To date 22 letters have been written to chapters asking for their program for publication in the TRANSACTIONS. We have received 4 replies. Three of the four chapters provided partial program material. One asked for assistance.

We have received a communication from the North Carolina Section informing us of the inactivity of the local PGA section. For this reason they disbanded this chapter. Secretary Cumming has placed it on the inactive list.

Although correspondence has been initiated between chapters and the committee asking for activity information little response has been received. It seems that there is little reporting made either to headquarters or to the committee although there is more activity than this response would indicate. It might be useful to have a form which could be used to inform the various committees of such activity.

Letters were also sent to sections which showed an increase in membership and were also over 25 in strength. This program has not proved very fruitful. Again each local section contacted lacks the leadership for organization. Some sections did reply but all felt there was not enough interest.

A number of items have been sent to the TRANSACTIONS for publication concerning chapter news. These are items of news received from various sections reporting their activities. It is hoped that from this reporting other sections may get ideas on program material.

WILLIAM M. IHDE

REPORT OF COMMITTEE ON CONSTITUTION AND BYLAWS

1) Our Chairman, C. M. Harris, feels strongly that any newly elected chairman of the Professional Group on Audio should have had some previous experience with the functioning of the group, preferably as a member of the Administrative Committee, and that the vice chairman should automatically become the next chairman.

In accordance with his wishes, we are submitting information on how this may be achieved.

Plan 1 is a block diagram outlining our present mode of electing the chairman or vice chairman.

Plan 2 is a block diagram showing how we may achieve our Chairman's wishes.

With the objective in mind that we wished to have the vice chairman also be the "chairman elect," the Constitution and Bylaws were reviewed. This review showed that a considerable number of changes, mostly of a minor nature, *i.e.* adding "Chairman Elect" after "Vice Chairman," would have to be made in both the Constitution and the Bylaws. If it is the wish of the Administrative Committee to have such a change, the necessary revisions will be worked out.

2) In reviewing the Constitution and Bylaws, there was some uncertainty uncovered with respect to membership status of the chairman on the Administrative Committee. In this connection Chairman Harris desires that the chairman be a member of the Administrative Committee but not exercise his right to vote except to break a tie.

3) It has been proposed that the past chairman remain a member of the Administrative Committee *ex officio* and without vote for a period of one year after the end of his term of office. This would provide for an improved continuity of PGA administratorship.

Summarizing, the Constitution and Bylaws Committee would like to have the members of the Administrative Committee vote for approval on these three items.

1) It is moved that the vice chairman also be designated as "Chairman Elect" and automatically become the next chairman of the Group. This is in accordance with Plan 2.

2) It is moved that the chairman be a member of the Administrative Committee but not exercise his right to vote except to break a tie.

3) It is moved that the past chairman remain a member of the Administrative Committee *ex officio* and without vote, for a period of one year after the end of his term of office.

H. E. ROYS
B. B. BAUER
D. W. MARTIN

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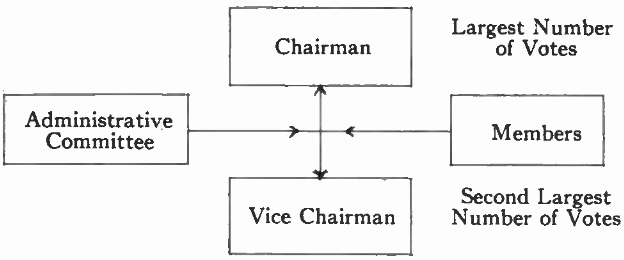
Election of Chairman and Vice Chairman

Plan 1

Present Mode of Operation



Source:

Chairman and Vice Chairman

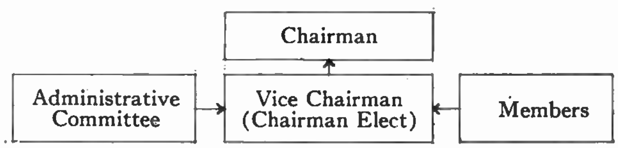
1) From the Administrative Committee.
2) From the Group.
   a) Nomination Committee with approval of Administrative Committee.
   b) By petition signed by 25 members.

Disadvantage:

Possible that chairman and vice chairman may be elected who have not had previous experience in administration and functions of the Audio Group.

Plan 2

Suggested Mode of Operation



Source:

Chairman

1) Vice Chairman during the last term.

Vice Chairman

1) From the Administrative Committee.
2) From the Group.
   a) Nomination Committee with approval of Administrative Committee.
   b) By petition signed by 25 members.

Advantage:

Chairman has served as Vice Chairman for one year with the knowledge that he will become the next Chairman.

REPORT OF THE EDITORIAL COMMITTEE

In March of this year the Editorial Committee was reorganized with Associate Editors in charge of various fields of audio as follows:

Field	*Associate Editor*
Acoustics, Speech, Music, Noise	D. W. Martin
Circuits and Components	A. B. Bereskin
Instrumentation	W. H. Ihde
Recording and Reproduction	B. B. Bauer
Special Features and News	H. C. Hardy
Systems and Applications	J. R. Macdonald
Transducers	P. B. Williams

Associate Editors have primary responsibility in their own fields for having papers reviewed and corresponding with the authors until the manuscript is in publishable form. Also they should be on the lookout for new papers, and should contact prospective authors of papers.

An excellent job has been done in handling of papers already submitted to PGA, and we are grateful for easing of the burden that was formerly carried by the Editor.

Individual members of the committee have not been too successful in finding new papers for TRANSACTIONS. For the most part we have relied on IRE convention papers, and on authors who sent papers to the Editor of their own accord. We should note, however, that the editorial committee is well represented in the list of authors. Fortunately there is a backlog of papers for approximately two issues. We are trying to maintain a rate of six technical papers per issue.

In regard to editorial content we feel that, in addition to the specialized articles, TRANSACTIONS ought to contain more feature material of general interest to all readers. Dr. Hardy, Editor for Special Features and News, is trying to find someone who will review events and developments outside of the U.S.A. on a regular basis. In the past, we had a section on "With Other Acoustical and Audio Groups" written by B. Bauer. Book reviews and patent reviews have been considered. We still hope that *The Editor's Corner* can be expanded into an open forum to air the views of members on subjects connected with audio, engineering, etc. Several provocative articles have been written with this in mind, but the response has been meager to date; audio engineers seem to be a passive group. Further proposals as to worthwhile features will be welcomed.

The present makeup of TRANSACTIONS is excellent. There has been some dissatisfaction with miniaturization of illustrations, especially those which contain a large amount of data. Headquarters has been advised, and we hope this will be remedied in the future.

The perennial problem of lateness of issues is still present. Headquarters has been reducing their processing time but one author can hold up an issue if he is tardy in supplying omissions in his article. If the lead time is 12 weeks for example, then the items for the November-December issue must be sent to headquarters in August. At least an additional month should be allowed for review and correspondence with authors. In the past we did not have an adequate backlog of papers to allow such a long lead-time.

Despite these problems, TRANSACTIONS has improved steadily and we appreciate suggestions for further improvement.

MARVIN CAMRAS
Editor

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MINUTES OF THE MEETING OF THE ADMINISTRATIVE COMMITTEE

Saturday, November 11, 1961—Cincinnati, Ohio

Members Present

R. W. Benson
A. B. Bereskin
D. E. Brinkerhoff
C. M. Harris, *Chairman*
H. E. Roys, *Vice Chairman*
B. B. Bauer, *Secretary-Treasurer*

Members Absent

F. Comerci
J. R. Macdonald
P. C. Goldmark
H. S. Knowles
W. C. Wayne

Guests Present

M. Camras
W. M. Ihde
D. W. Martin

Reading and Approval of the 1962 Estimated Budget

The Secretary-Treasurer read the 1962 estimated budget (below) which projects total receipts for the year at $14,433, total expenditures of $15,600, and a remaining balance of $12,833. It was pointed out that the IRE wishes to see the PGA balance reduced in line with the group expense. By motion of R. W. Benson, seconded by W. M. Ihde, the proposed budget was accepted unanimously.

Reading and Approval of Committee on Chapters and Membership

Report was presented by Chairman W. M. Ihde (below). Letters have been sent to chapters, but there are signs that only few are active. Chapter News is being published so that various sections may get ideas on program material. By motion of A. B. Bereskin, seconded by M. Camras, it was moved unanimously to approve and accept this report.

Report of the Nominations Committee

Report of Chairman Martin was read and discussion held on the Administrative Committee membership status of Michel Copel as affected by the last constitutional amendment. Recommendation of Chairman Martin to add the name of Mr. Copel to the list of candidates for Chairman or Vice Chairman was approved, together with the report, upon motion by W. M. Ihde and M. Camras, by unanimous vote. (*See resulting ballot, above*).

Report of Committee on Constitution and ByLaws

Report by Chairman Roys is enclosed, proposing the following constitutional amendment:

a) Make the Vice Chairman the Chairman Elect.
b) Restore the Chairman to the membership of the Administrative Committee, but without a vote except to break a tie.
c) Retain the past Chairman as a member of the Administrative Committee, *ex officio*, for a period of one year after the end of his term in office.

By motion of A. B. Bereskin, seconded by R. W. Benson, the report was accepted unanimously, with the instructions to the committee to incorporate the above changes in the constitution for a vote by January 1.

Report of the Editorial Committee

Marvin Camras, Chairman, presented a report announcing reorganization of the Editorial Committee into seven fields each in charge of an Associate Editor. It is hoped that this will relieve the problems of finding suitable technical papers.

The report (below) was unanimously accepted upon motion of A. B. Bereskin and R. W. Benson.

Next Meeting

It was agreed to hold the next meeting of the Administrative Committee in New York on Tuesday evening, March 27, 1962, of the IRE International Convention.

Adjournment

The meeting was adjourned at 11:00 P.M.

BENJAMIN B. BAUER
Secretary-Treasurer

1962 ESTIMATED BUDGET

January 1, 1962 to December 31, 1962

1) Balance from December 31, 1961		$14,000.00
Receipts During Period:		
2) IRE Subsidy (⅓ of item 10):	$ 4333.00	
3) Membership Fees	8600.00	
4) Advertising	500.00	
5) Sale of Publications	1000.00	
6) Surplus from Meetings	——	
7) Other Sources	——	
8) Total Receipts		$14,433.00
9) Total Balance and Receipts		$28,433.00
Expenses During Period:		
10) Publications	$13,000.00	
11) Membership Service Charges	500.00	
12) Group Awards	500.00	
13) Editorial Administrative Expenses	100.00	
14) Others	1500.00	
15) Total Expenses		$15,600.00
16) Balance as of December 31, 1962		$12,833.00

BENJAMIN B. BAUER
Secretary-Treasurer

World Radio History

Absolute Measurements of Magnetic Surface Induction*

FRANK A. COMERCI†, SENIOR MEMBER, IRE

Summary—Two methods have been used for obtaining an absolute measurement of normal surface induction of a medium wavelength signal recorded on magnetic tape. One employs a nonmagnetic loop and an electrical procedure for determining its active rectangular cross-sectional dimensions. The normal surface induction is computed from these dimensions and the output voltage induced in the loop as the tape is transported at a prescribed speed across the active portion of the loop. The other is based on recording a dc signal of current level equal to the rms value of the ac recording current which produces the equivalent recorded signal as that for which the measurement is desired. A calibrated search coil is then used to measure the total remanent flux in a bundle of many layers of the dc recorded tape. The surface induction is then calculated for medium wavelength signals using existing formulas

Measurements of surface induction obtained using the two methods provide equivalent results. The surface induction could be measured for a wide range of wavelengths using the nonmagnetic loop.

Introduction

Several years ago a nonmagnetic loop was shown[1] to be an adequate tool for measuring the surface induction of a relatively long recorded wavelength. Using this measurement, the surface induction for other wavelengths could then be determined using the "short gap method" for measuring relative levels. A subsequent article[2] stated that the nonmagnetic loop measures the surface induction for the case where the tape is suspended in a unit permeability material, such as air, whereas in actual use the tape is in contact with a highly permeable reproducing head and a measurement simulating this condition is preferred. A measuring procedure was then described which provides a measure of the intensity of magnetization within the tape coating in terms of millimaxwells per millimeter of track width.

Details of the two methods have been adequately described in the literature. Actually in either method of measurement, the magnetized tape is surrounded by air or a medium of unit permeability. When using the nonmagnetic loop, the field strength existing at the surface of the tape is measured directly and the intensity of magnetization within the tape coating can be calculated if the effective tape dimensions are known. The flux lines or millimaxwells through the tape cross section could be calculated directly. For the search coil method, the flux lines through the tape cross section are measured and the resulting surface induction for a relatively long recorded wavelength could be easily calculated. Any difference in measurements performed by the two methods, excluding experimental error, would then reflect on the validity of the formulas used for calculation.

A short experiment was conducted to investigate possible differences in the measurements. The results were essentially the same. However, an analysis of the data revealed a graphical technique which, under the conditions employed, was able to separate the magnetic losses.

Procedure

Measurements of normal surface induction were obtained by the nonmagnetic loop and the search coil techniques for a single sample of magnetic recording tape at several bias and signal levels. The results were then compared. The data was then examined to determine if the losses could be segregated. The nonmagnetic loop results were then used to obtain measurements of surface induction for a wide range of wavelengths and to calibrate a magnetic reproducing head.

For the nonmagnetic loop measurements, a loop was constructed as shown in Fig. 1. Two rectangular blocks of polishable insulating material were fabricated to $\frac{5}{16}\times\frac{5}{8}\times\frac{7}{8}$ inch dimensions. The larger surfaces intended to mate when the two blocks were clamped together were ground and polished optically flat. Two grooves were then milled close to the long edge of the polished surface of one block of sufficient size to accept copper conductors which formed the rear portion of the loop. A piece of platinum foil 1 micron thick was then cemented over the polished surface of the milled block bridging the front ends of the two conductors. The foil was soldered to the two conductors at the junction points. The rear portion of the foil was then ground away to a distance 10 mils from the front edge of the block. In performing this operation a deeper cut was made near the edges of the block to form a reference mark locating the rear (covered) edge of the foil. The two blocks were then bolted together with the polished surfaces mating. The front surface of the structure was then ground to a $\frac{1}{2}$ inch radius parallel with the anticipated foil edge to a point where the dimension of the platinum foil, front to back (d dimension), as determined by the distance from the front surface to the reference marks, measured 5 mils. The front surface was then hand lapped to a final finish. The cross-sectional dimensions of the remaining platinum material which formed the active part of the

* Received April 6, 1962. To appear in the 1962 IRE International Convention Record, pt. 7.

† CBS Laboratories, Stamford, Conn.

[1] R. Schwartz, S. Wilpon and F. A. Comerci, "Absolute measurement of signal strength on magnetic recordings," *J. SMPTE*, vol. 64, pp. 1–5; January, 1955.

[2] O. Schmidbauer, "Zur Bestimmung der Magnetisierung auf Tonband," *Electronic Rev.*, vol. X, pp. 302–305; October, 1957.

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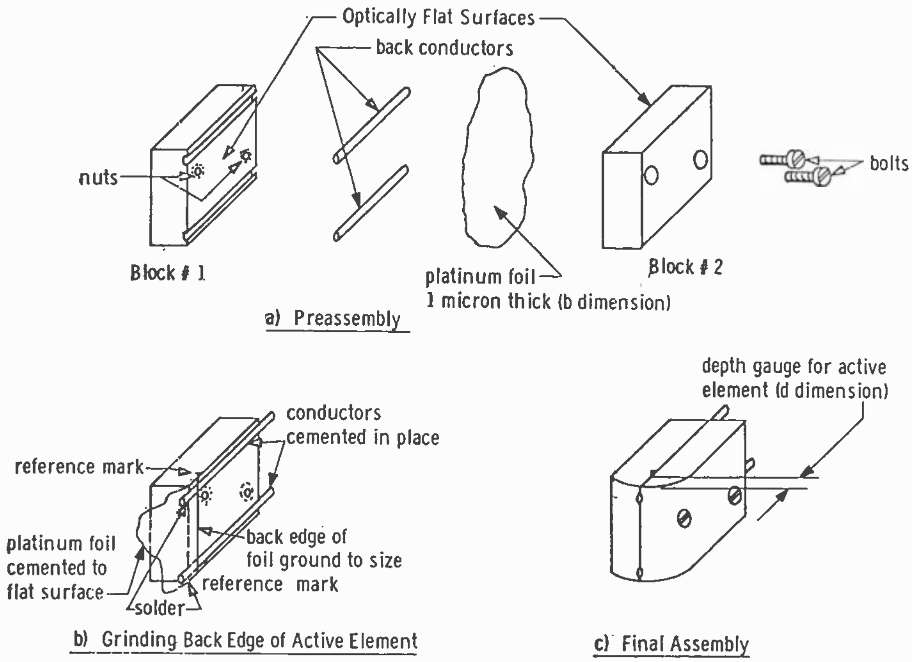

Fig. 1—Construction of nonmagnetic loop.

loop were measured by microscope to be approximately 4.5 mils deep (*d* dimension) and 1 micron (39 micro-inches) broad (*b* dimension).

A sample of 150-mil-wide magnetic recording tape known to have an exceptionally smooth flat surface and a coating thickness of 0.35 mil, was selected for the measurements in an effort to avoid excessive head-to-tape spacing and thickness loss. Full track recordings were made on this tape at several wavelength increments from 93.5 to 0.187 mil. The recordings were made with constant signal current and a bias level (140 kc) which gave peak signal output for a wavelength of 0.935 mil. The tape speed used was 1.87 ips. This low speed was selected to avoid using unnecessarily high frequencies with corresponding electrical and core losses. The signal current used was that which resulted in 5 per cent distortion in the nonequalized playback output for a 0.935 mil recorded wavelength. This level is hereafter referred to as the "maximum recording level." The bias current will be referred to as "optimum bias." The record head was known to provide equal magnetizing fields for constant current input for the signal frequency range employed. It had a gap length of 2 microns. The optimum bias was judged to record through only 0.25 mil of the tape thickness on the basis of the ratio of the increase in output which could be achieved when the bias was increased for a long wavelength signal. This underbiased condition was used to meet restrictions of the search coil technique.

A playback head with a 1-micron gap was used to measure the output from the recorded tape. This head was of a design which had proved to be very stable over a use period of more than one year and could serve as a standard head after being calibrated.

The recorded tape was then operated on a 15-ips tape transport on which the nonmagnetic loop was mounted. The output voltage of the loop was measured for each recorded wavelength. In order to measure the extremely small voltages from the loop a high step-up-ratio transformer and appropriate band-pass filters were required in the measuring circuits. Calibration of the measuring circuit was achieved by introducing known voltages across a 1-ohm resistor in series with the loop and transformer primary. Even with this arrangement the low levels at longest and shortest wavelengths could not be measured because of the low SNR.

The effective depth of the active loop cross section was determined by methods described in the literature.[1] A plot of the loop output voltage vs recorded wavelength was made and the wavelength noted for an output which, in the longer wavelength direction, was 3 db less than that over the flat portion of the curve. The depth dimension was then calculated from the simple expression

$$d = 0.19\lambda_{3db}$$

where

d = depth dimension (mils)

λ_{3db} = wavelength for 3-db-long wavelength loss (mils).

The normal surface induction at a wavelength of 4.7 mils for which short wavelength losses could be neglected was then determined using the formula

$$By = \frac{e_{max} \cdot 10^8}{vw\left[\frac{1 - e^{\frac{-2\pi d}{\lambda}}}{\frac{2\pi d}{\lambda}}\right]}$$

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where

By = normal peak surface induction (gauss)
e_{max} = peak output of loop (volts)
v = tape velocity (cm/sec)
w = width of recording (cm)
d = depth dimension of loop (mils)
λ = wavelength (mils).

For the search coil measurement the same tape sample used for the nonmagnetic loop measurement was recorded using the same recording equipment but a dc record current equal to the peak value of the constant current maximum recording level used previously. Recordings were made for optimum bias conditions at four dc-current levels and at the maximum dc current level for four bias levels. The output of the playback heads was also measured when corresponding rms values of ac current to produce a 4.7 mil wavelength recording were used instead of dc current. These additional measurements were made to observe any differences between the normal head playback results and the search coil results for different shaped recorded wavefronts or direction of magnetization.

Each of the dc recorded sections representing the different bias and dc levels were cut into 30 five-inch lengths which were placed one over the other to form a bundle of 30 lengths. Care was exercised to be certain that the magnetizations of each length in the bundle were in the same direction. The bundle of samples were inserted into a search coil similar to that described in the literature.[3] The search coil was connected to an electronic integrating amplifier and meter. The bundle was then quickly withdrawn from the coil and the remanent flux ϕ_t in the bundle was read on the calibrated meter. The remanent flux ϕ for a single layer was then equal to $\phi_t/30$.

The surface induction at a wavelength of 4.7 mils was then calculated using the formula[3]

$$J_x = \frac{\phi}{4\pi WC} \quad \text{and} \quad By = \frac{4\pi^2 C J_x}{\lambda} \quad \text{from which}$$

$$By = \frac{\pi\phi}{w\lambda} \quad \text{is obtained}$$

where

By = normal surface induction in gauss
ϕ = remanent flux for tape cross section in Maxwells
w = active tape width in cm
λ = wavelength being considered in cm.

Results

The outputs of the playback head for the various constant current recorded wavelengths are shown in Fig. 2. Corresponding outputs for the nonmagnetic loop are shown in Fig. 3. The 3-db down point occurred at a wavelength of 24.2 mils from which the depth dimension of the loop was determined to be 4.6 mils.

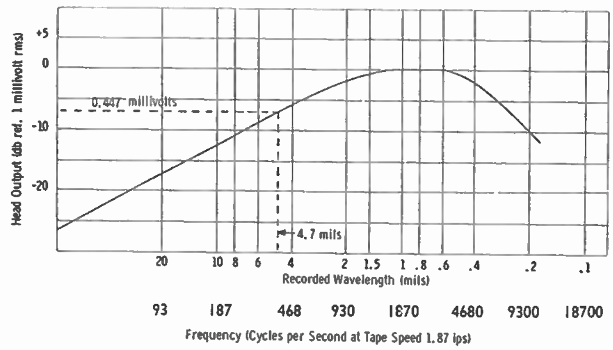

Fig. 2—Playback head output vs recorded wavelength.

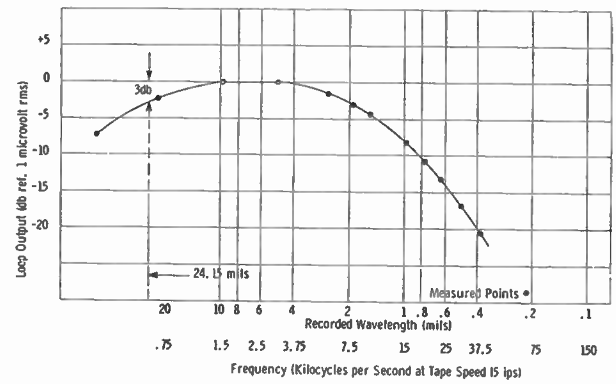

Fig. 3—Nonmagnetic loop output vs recorded wavelength.

The normal surface induction for a wavelength of 4.7 mils was then calculated to be 59.4 gauss peak.

From the search coil measurement the remanent magnetization in a single cross section of tape was found to be 0.256 Maxwell. The corresponding surface induction for a signal wavelength of 4.7 mils was calculated to to 60 gauss peak. The surface induction values determined by the two methods were therefore in close agreement. The playback head could then be considered to be calibrated for the 4.7 mil wavelength as having a sensitivity of 7.5 microvolts rms output per gauss of peak surface induction or 94.0 gauss per millivolt output.

The results of measurements made for the various signal and bias levels are shown in Table I. The agreement between surface induction measurements obtained from the calibrated head and the search coil indicate that at least for an oriented tape there is little difference in results for the two methods of measurement.

It should be noted that the search coil only measures the longitudinal component of magnetization whereas the playback head output is a function of both longitudinal and perpendicular components. For the oriented tape it might be expected that the major magnetization component will be in the oriented longitudinal direction. If an appreciable portion of magnetization were perpendicular as would be expected from higher bias levels the results obtained for the search coil would be lower than those for the calibrated head.

[3] I. Levine and E. D. Daniel, "Magnetic properties of magnetic recording tape," *J. Acoust. Soc. Am.*, vol. 32, pp. 1–15; January, 1960.

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TABLE I
MEASURED NORMAL SURFACE INDUCTION FOR VARIOUS RECORDING AND BIASING LEVELS

Bias Level Per Cent of Optimum Level	Record Level Per Cent of Maximum Level	Playback Heat Output, rms (millivolts)	Peak Surface Induction Gauss	
			Head Cal.	Search Coil
100	100	0.447	59.4	60
100	71.4	0.316	42.7	45
100	50	0.238	32.2	32.2
100	37	0.167	22.5	22.4
137	100	0.5	67.5	68.7
70	100	0.399	53.5	54.5

SURFACE INDUCTION AT SHORT WAVELENGTHS

The short-gap method is often used to obtain a measure of relative surface induction as a function of wavelength. This relative calibration together with the absolute measurement could be used to obtain an absolute measure of surface induction for all wavelengths. For the extremely short wavelengths being investigated and the 1 micron gap reproduce head employed in these experiments, it was impossible to detect a null point resulting from the gap effect. It was therefore attempted to use the magnetic loop to measure surface induction at short wavelengths.

The normal surface induction for a recorded signal on a tape is defined as the flux density appearing at the surface of the tape in a direction normal to the surface when the tape is suspended in a material (air) of unit permeability. For a recording of constant magnetization in the longitudinal direction at various wavelengths and wavefronts parallel to the tape cross section, losses have been adequately analyzed. When using a magnetic recording head, four wavelength dependent losses are encountered in the playback process:

1) Azimuth
2) Gap length effect
3) Spacing
4) Tape thickness.

Azimuth losses are usually small enough to be neglected for carefully fabricated heads. The 1-micron gap length of the playback head and the nonmagnetic loop used in these experiments would introduce only a minor loss at the wavelength of interest. Although spacing loss was held to a minimum by careful polishing of tape and head surfaces, an appreciable spacing loss could be expected.

Tape thickness loss, sometimes referred to as self-demagnetization loss, was expected to be the predominant factor in the short wavelength response.

On examining the curve of Fig. 3, it should be noted that at short wavelengths the curve changes shape at two points, one at a wavelength of about 4 mils and another at a wavelength of about 1.5 mils. It should be realized that for perfect recording and zero playback losses the output of the nonmagnetic loop should be constant for wavelengths appreciably shorter than the *d* dimension of the loop. The inflection points noted should bear a clue to the nature of losses which account for the falloff in output at short wavelengths.

If one were to examine curves of spacing loss and thickness loss as available in the literature, it would be observed that, as wavelength decreases, a small loss is gradually encountered. Beyond a particular wavelength the loss increases at a greater rate. It is considered that this change of rate of loss is connected with the change of shape noted in the curve of Fig. 3. The first shape change was considered as resulting from one loss, the second by another loss. Thus, if the curve were corrected by the first loss, a flattening of the curve should be achieved in the region between the two points of inflection. Correction by the second loss would then flatten the curve beyond the second point of inflection.

By trial and error, it was found that only thickness loss and one particular value of tape thickness would provide a thickness loss correction which would flatten the curve between the two inflection points without causing the output to exceed that in the original flat region (over correction) or cause undesirable irregularities in the curve. This value of thickness was found to be 0.25 mil which agrees with that judged previously to be the effective tape coating thickness. In Fig. 4 the output curve for the nonmagnetic loop is shown corrrcted for this thickness loss.

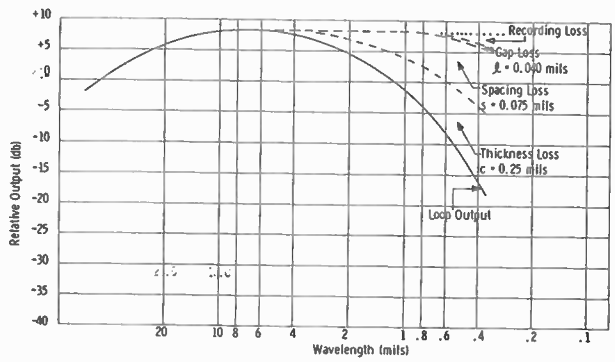

Fig. 4—Loss separation for nonmagnetic loop.

Next, by trial and error, a value of spacing was found to explain the departure of the thickness loss corrected curve from a flat output. A spacing loss of 0.075 mil was found to best account for this departure. Corrections for this spacing and also a *b* dimension of 0.040 mil, the thickness of the platinum loop, are also shown in Fig. 4. The departure of the final corrected curve from flat output was considered to be due to recording losses. Thus, the recording, at least for those layers of tape coating thickness contributing to playback output, could be considered to be perfect to a wavelength of about 0.75 mil. It is interesting to note that this is the wavelength at which bias was adjusted to give maximum output. At the shorter wavelengths, the recording losses are in close agreement with the difference in short wavelength out-

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A Study of the Chemical and Physical Properties of Magnetic Recording Tape*

F. NESH† AND R. F. BROWN, JR.†, MEMBER, IRE

Summary—**A study has been made of the chemical and physical properties of magnetic recording tape. The chemical studies indicate the possible relationship between a series of solvent tests and the wear properties of commercially available tapes. The physical studies, including electron micrographs, indicate a smaller unit crystal size for γ-ferric oxide than previously supposed and a relationship between a better dispersion and improved magnetic properties. Both studies are being continued in greater detail.**

A STUDY HAS been made in this laboratory of the properties, both chemical and physical, of magnetic recording tape which has resulted in some very interesting effects and observations which we intend to investigate further in greater detail.

The chemical studies were directed along two lines, binder solubility studies and quantitative analyses of the tape coatings. Twenty-five commercially available tapes were tested as to their relative solubilities in 6 of the more common organic solvents, and classified as to degree of binder solubility. In addition samples of different batches of the same type tapes, which had proved to wear differently in actual use, were compared in the solubility tests. Of the latter, those samples which proved poorer in use were also less resistant to the solvents. By "poorer in use" we mean that the coating came off the backing and adhered to the heads, thus clogging the heads and also cutting down on the life of the tape. This can be explained by noting that the resins and adhesives used in the binder are of high polymer structure. Longer chains and more closely linked side chains result in fewer active groups being available for reaction with the solvents. We conjecture that the tie-up of these active groups in the chains makes the binder less subject to solvent action and more resistant to heat and friction, and consequently to wear.

* Received March 2, 1962. This work was performed under Contract No. AF(08-606)61-1237 from Patrick Air Force Base.

† National Bureau of Standards, Washington, D. C.

At present this laboratory is undertaking a detailed study of the binder solubility characteristics of tapes submitted by various other Government agencies and stations, for which are available wear test data on the identical samples both under laboratory and field conditions. It is hoped that a thorough study of the combined data may yield pertinent information. We hope to publish the results of these studies when they are completed.

The results from quantitative chemical analysis of seven tapes are given in Table I. Spectroscopic analysis showed iron as the only element present in more than very small trace amounts and X-ray crystallography showed only gamma ferric oxide in the inorganic portion of the coating (less than 5 per cent alpha ferric oxide cannot be detected in gamma ferric oxide).

TABLE I

SOME BULK PROPERTIES OF MAGNETIC TAPES

	A	B	C	D	E	F	G
Weight of coating (mg/cm)	2.40	2.32	2.12	2.09	1.69	1.34	1.30
Weight of oxide (gamma Fe_2O_3) (mg/cm)	1.85	1.69	1.81	1.46	1.30	1.02	1.02
Coating thickness (microns)	14.7	13.2	16.8	12.7	9.9	8.9	8.9
Weight oxide per volume coating (g/cc)	1.98	2.02	1.70	1.81	2.07	1.81	1.81
Remanent flux (Maxwells)	0.86	0.75	0.83	0.64	0.57	0.62	0.62
Remanent merit (Maxwells/mg/cm)	0.46	0.44	0.46	0.44	0.44	0.61	0.61
Retentivity (gauss)	920	900	780	790	910	1100	1100

The physical studies on the magnetic tapes involved magnetic remanent flux measurements. These are shown in Table I. A correlation of the magnetic properties with the gamma ferric oxide content is also shown in Table I, as "Remanent merit." As will be noted, tapes F and G showed more remanent flux per weight of ferric oxide than the other tapes. (These 2 tapes were from the same manufacturing company.) Since the spectroscopic and X-ray diffraction studies ruled out either magnetic doping by some added substance or dilution by some impurity the only other possible explanation was a difference in particle size, preorientation, shape, or dispersion, or any combination of these. Consequently electron microscopy studies were undertaken with quite interesting results. Electron micrographs were made of three commercial tapes both of the oxide after removal from the tape and of the tape surface by replication. The replication technique used involved first shadowing the tape surface at a 35° angle with palladium and then replicating with carbon. After this the entire tape was removed by dissolving it away. The backing and inert matter were dissolved in organic solvents, and the iron

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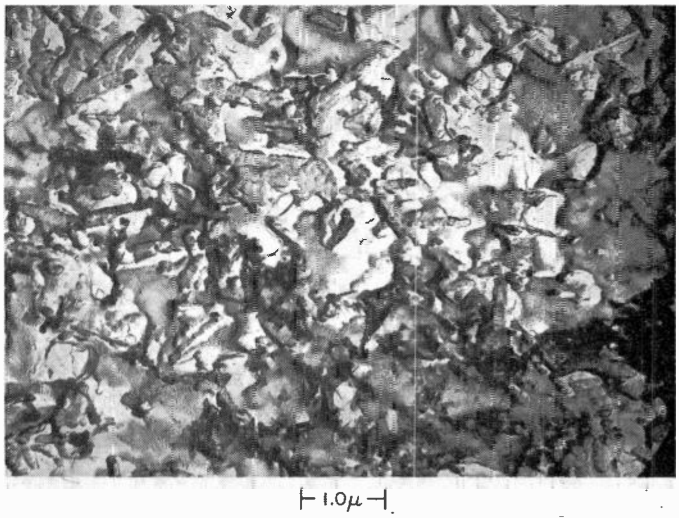

Fig. 1—A replicate of the surface of tape D at 10,000×direct magnification.

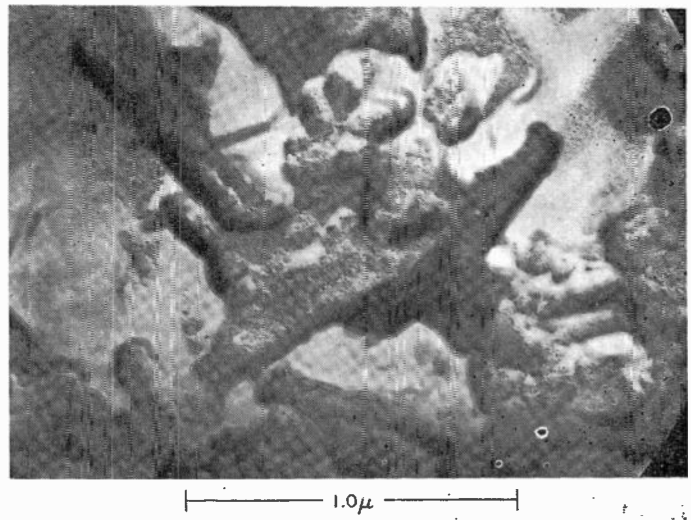

Fig. 3—A replicate of the surface of tape D at 40,000×direct magnification.

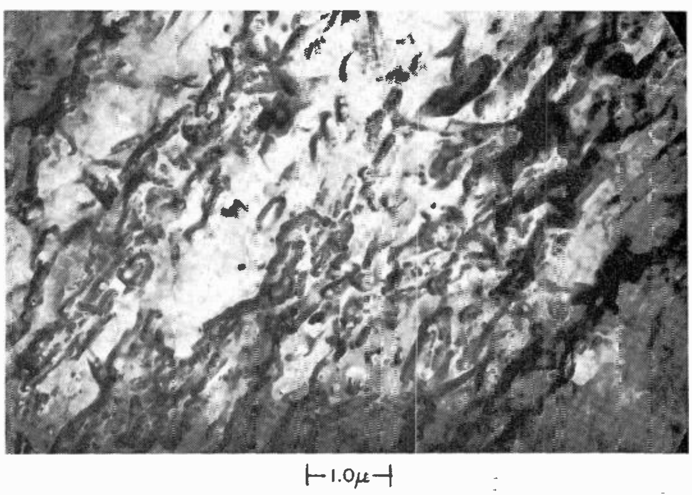

Fig. 2—A replicate of the surface of tape G at 10,000×direct magnification.

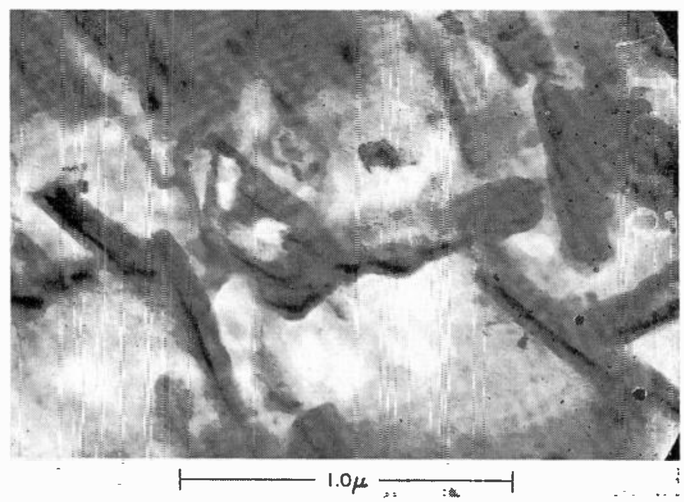

Fig. 4—A replicate of the surface of tape G at 40,000×direct magnification.

oxide in HCL. The pictures of the oxide after removal from the tape were the same in all three cases and showed the same particles to be the same in shape (acicular crystals) and size (approximately 0.5 to 0.6 μ by 0.1 μ) as already known. The surface replications however showed interesting pictures. Fig. 1 shows a replicate at 10,000× direct magnification of the surface of tape D. Fig. 2 shows a replicate at 10,000× direct magnification of the surface of tape G. As can be easily seen, Fig. 1 shows only a slight particle alignment while Fig. 2 shows a rather complete particle alignment. Fig. 3 shows a replicate at 40,000× direct magnification of the surface of tape D and Fig. 4 shows a replicate at 40,000× direct magnification of the surface of tape G. Fig. 4 shows the most interesting observation of all. Not only are the oxide particles more dispersed but the individual particle, at first sight, appears to be half the width of what was previously supposed to be the smallest gamma ferric oxide particle. Its average measurement is 0.5 to 0.6 μ by 0.06 μ. Those particles which measure 0.5 by 0.1 μ can be seen to be double crystals. On closer examination of several of the narrower particles one can seen indications that these in turn may be composed of three crystals, making the unit crystal a very narrow needle indeed. Apparently the presence of a thin plastic coating over the surface of the crystals inhibits a sharp replication and shadowing. At present studies are being conducted on surfaces from which this thin plastic coating is being removed in order to get clearer pictures of what the unit crystal might actually be. Also being conducted are studies of the relationship between this ultimate crystal dispersion and magnetic properties both in the laboratory and in field use.

ACKNOWLEDGMENT

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New Approaches to AC-Biased Magnetic Recording*

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Summary—**Ac-biased magnetic recording is described in a brief analysis based upon the anhysteretic magnetization process. Several different models are used to illustrate particular aspects of the recording process. It is shown that, using conventional record heads, there is bound to be a conflict between the efficient recording of short and long wavelength signals. The critical requirements involved in recording 15 kc at as low a tape speed as $1\frac{7}{8}$ ips are emphasized by pointing out that, on reproduction, 75 per cent of the output comes from the first 0.7 micron (28 microinches) of the coating.**

Various methods for improving the record process have been proposed from time to time. These methods consist of proposals for sharpening the recording field as a whole, sharpening the bias field alone, and increasing the uniformity of the recording field through the coating thickness. The design of heads to accomplish any of these objectives remains to be worked out in detail. However, several possible techniques are discussed, namely pole-shaping, eddy-current shielding and the use of poles on both sides of the tape.

An entirely new recording technique is described which utilizes successive recordings by two separate gaps of different sizes. The two gaps can be contained in separate heads or in a single head, provided that the time-delay between the two recordings, if significant, is compensated for prior to recording. The principle is simple. The long gap is fed only with low-frequency signals which it can record effectively throughout the whole coating; the short gap records the high-frequency signals in the outermost layer of tape. The bias field from the short gap need not significantly reduce the level of the low-frequency recorded information. Filtering requirements and methods of time-delay compensation are discussed in the text, and a mathematical analysis is given of the interference to be expected from an uncompensated system.

Review of Conventional AC-Biased Recording

Field from a Ring Head

THE LEAKAGE field from the gap of a conventional recording head has been analyzed in some detail.[1–6] The field distribution is complex, and there are a variety of ways in which graphical representations can be constructed. No single representation is capable of displaying all the information required for an analysis of recording. In fact, too much concentration on one representation can give rise to misleading conclusions. For example, a plot on longitudinal and perpendicular component field strengths of the type shown in Fig. 1(b) is very useful, but only as long as it is fully realized that components are mathematically convenient rather than physically significant. From many points of view the plot of resultant field strength at various distances above the gap, shown in Fig. 1(a), is more valuable. Among other things, it shows more clearly that elements of tape passing close to the head (separation less than a third of the gap length) receive two field maxima, rather than a single maximum, these maxima occurring when the element passes above the two edges of the gap.

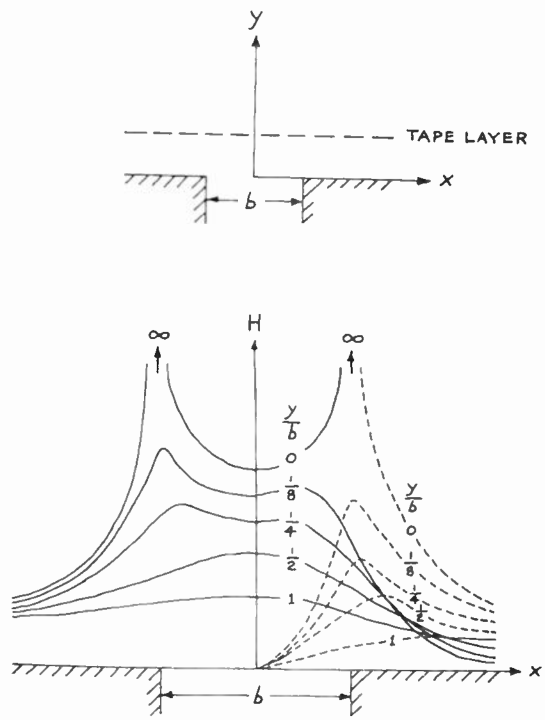

Fig. 1—Distribution of recording field. (a) Resultant field. (b) Longitudinal (solid) and perpendicular (dashed) components.

The way in which the direction of the resultant field changes, as an element traverses the head, is best illustrated by polar diagrams of the type shown in Fig. 2. The field is represented as a vector of length proportional to field strength and orientation relative to the direction of tape motion. The vector traces out one of the curves shown, depending upon the depth of the element within the coating. For far layers of coating, the vector traces out a circular path, the field strength being a maximum in the longitudinal direction (in the central plane of the gap) and vanishingly small in the perpendicular directions. For near layers, the curves become butterfly-shaped, the field maxima (above the gap edges) being at ±45° if the gap edges are perfectly sharp.

* Received March 23, 1962. The work described in this paper was performed while both authors were with the Ampex Corporation Research Laboratories, Redwood City, Calif.

† Memorex Corporation, Santa Clara, Calif.

1 A. D. Booth, *Brit. J. Appl. Phys.*, vol. 3, pp. 307–308; 1952.

2 W. K. Westmijze, *Philips Res. Repts.*, vol. 8, pp. 148–183; 1953.

3 O. Karlqvist, *Kungl. Tekniska Hogskolans Handlingar*, No. 86, pp. 3–27; 1954.

4 J. Greiner, *Nachrichtentechnik*, vol. 5, pp. 295–298, 1955; and vol. 6, pp. 63–70; 1956.

5 G. Schwantke, *Acustica*, vol. 7, pp. 363–369; 1957.

6 S. Duinker, *Tijdschr. ned. Radiogenoot.*, vol. 22, pp. 29–48; 1957.

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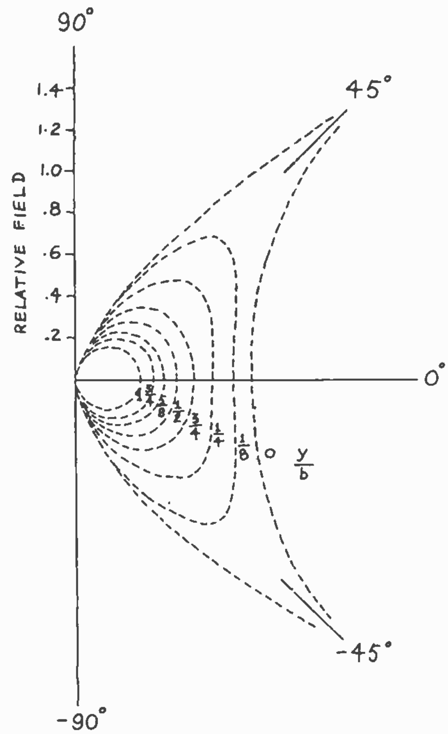

Fig. 2—Loci of resultant field vector applied to various layers of tape.

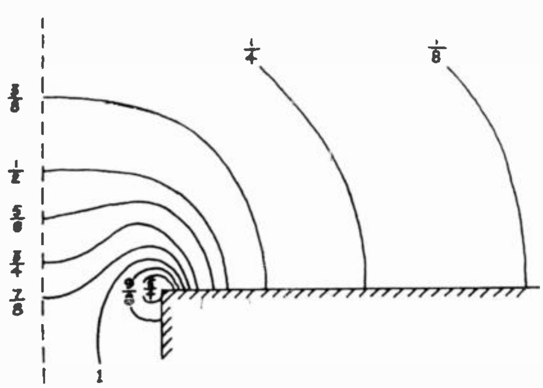

Fig. 3—Contours of equal resultant field strength, relative to the strength deep within the gap.

Finally, there is a third way of plotting the field distribution, which is particularly valuable in analyzing ac-biased recording. This representation consists of drawing contour lines of constant resultant field strength, as shown in Fig. 3. The contour lines are crowded in the neighborhood of the gap edges, but become more spread out further away from the gap until, at distances large compared with the gap length, the contours become semicircles about the gap center plane.

Reproduction from Various Parts of the Coating

It is clear from the recording field plots that the tape coating will not be recorded uniformly throughout its depth c. Even if it were, the relative importance of a given layer on reproduction depends upon its position within the coating to an extent depending upon the recorded wavelength λ. If the total reproduced output is E, a layer of thickness y at the surface of the coating contributes an amount e where

$$\frac{e}{E} = \frac{1 - \exp(-2\pi y/\lambda)}{1 - \exp(-2\pi c/\lambda)}.$$

This expression is readily derived from the well-known exponential law (54.5 db/wavelength) governing the loss caused by separating a recorded layer from the reproducing head. When λ is less than 1.5 c, the expression reduces to

$$e/E = 1 - \exp(-2\pi y/\lambda)$$

to within 1 per cent, and the output becomes independent of coating thickness. Under these conditions, 75 per cent of the reproduced output comes from a surface layer of thickness y_0 where

$$0.75 = 1 - \exp(-2\pi y_0/\lambda)$$

or

$$y_0 = 0.22\lambda$$

Taking, as an example, a 15-kc signal recorded at $1\frac{7}{8}$ ips, λ is 0.125 mil, and y_0 is equal to 0.028 mil. In other words, under these conditions, *75 per cent of the output comes from the first 28 microinches, or 0.7 micron, of the coating.* It is instructive to compare this dimension with the average size of the oxide particles, generally about 0.7×0.1 micron.

Tape Magnetic Properties

The basic mechanism of ac bias is readily explainable as an example of anhysteresis.[7,8] The anhysteretic magnetization process consists of applying, in addition to a small unidirectional field (analogous to the signal field), a large alternating field (analogous to the bias field) which is reduced gradually to zero before removing the unidirectional field. If the amplitude of the ac field is sufficiently high, a plot of remanence vs dc field strength yields a curve which is initially very linear and of high slope. In a similar way, ac bias linearizes and increases the sensitivity of the recording process.

The most important anhysteretic magnetization curve is that showing the variation of remanence with initial ac amplitude, using a small value of dc field strength well within the linear range. The type of curve obtained is illustrated in Fig. 4, curve (a). The curve rises steeply as the bias amplitude approaches the coercive force. During the reduction of the bias field from a high initial strength, the remanence is acquired progressively as the amplitude of the bias field falls through a "critical range." The relative amount of remanence acquired as the bias falls by successive increments is proportional to the derivative of the

[7] W. K. Westmijze, *Philips Res. Repts.*, vol. 8, pp. 245–269; 1953.
[8] E. D. Daniel and I. Levine, *J. Acoust. Soc. Am.*, vol. 32, pp. 1–15; 1960, and vol. 32, pp. 258–267; 1960.

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curve of the remanence vs bias, implying a bell-shaped weighting curve centered approximately about the coercive force. As a first approximation, however, we can consider the remanence to be acquired uniformly as the bias amplitude falls between the values H_2 and H_1, shown in Fig. 4. In practice, the ratio H_1/H_2, when estimated by the method indicated in Fig. 4, is at best about $\frac{3}{4}$. The mean value $\frac{1}{2}(H_1+H_2)$ is normally approximately equal to the coercive force H_c.

The only major difference between anhysteresis as described above and ac-biased recording is that the signal and bias fields fall simultaneously, rather than separately, as an element of tape leaves the precincts of the gap. The analogous anhysteretic magnetization curve, when the fields fall together, is shown by curve (b) of Fig. 4. Instead of reaching a constant value at high-bias amplitudes, the magnetization goes through a maximum at a value of bias some 20 per cent greater than the coercive force.

The reason for this behavior is simply that, by the time the bias has decreased to the critical range from some high initial value, the signal field strength has also decreased in the same ratio. Consequently, using very high initial values of bias, the remanence tends to become inversely proportional to the initial bias amplitude.[8] From most points of view, the first type of anhysteretic curve is the more valuable. The discrepancy between ordinary anhysteresis and recording is not fundamental and is removed so long as we consider the effective strength of the signal field to be that existing in the region where recording takes place. It should be noted, however, that a means of recording in which the bias field falls below H_1 before the signal field appreciably decreases, would have distinct advantages over conventional recording. In particular, the bias adjustment would no longer be critical (at least as far as long wavelength recording is concerned), and some of the problems of "over-biasing" would no longer be encountered. It would be more feasible to produce a coating uniformly magnetized throughout its depth.

A final point of considerable importance concerns the variation of anhysteretic properties with the direction of the applied fields using tapes having the usual degree of particle orientation.[9] The types of result obtained are illustrated in Fig. 5. Curve (a) corresponds to magnetization along the direction of orientation (parallel to the length of the tape), and curve (b) corresponds to magnetization in a perpendicular direction. For a given signal field strength, the remanences obtained in the two directions are in the ratio of approximately 4:1. A very important point, however, is that the critical bias range is substantially the same in the two cases. Measurements of coercivity show that it,

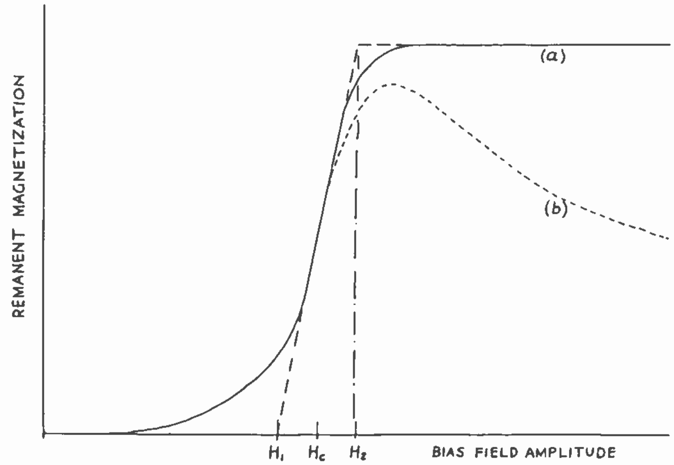

Fig. 4—Anhysteretic magnetization curves for a small signal field. (a) Bias reduced to zero before signal. (b) Bias and signal reduced to zero together.

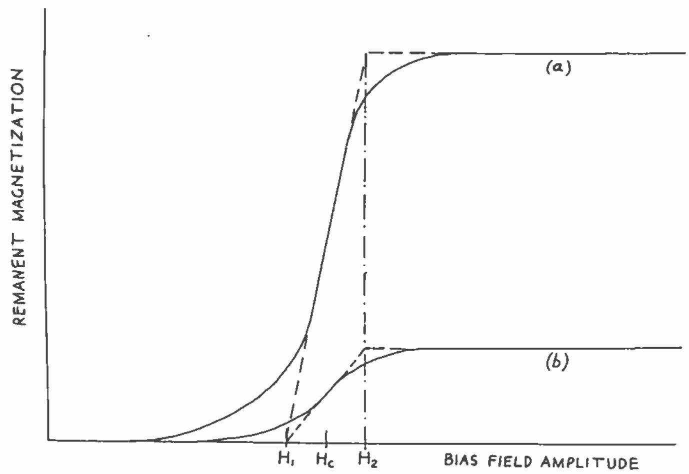

Fig. 5—Anhysteretic magnetization curves for a small signal field. (a) Bias and signal field parallel to tape length. (b) Bias and signal field perpendicular to tape length.

too, is substantially independent of the direction of orientation. One of the conclusions to be drawn from the coercivity results is that approximately the same degree of erasure should be produced when an erasing field of given internal strength[10] is applied in any direction.

Long vs Short Wavelength Recording

For a given bias current through the head (or bias field strength deep within the gap), the decrease in bias amplitude from H_2 to H_1 occupies a certain region in space. It scarcely needs pointing out that the greatest recording resolution is achieved by making the longitudinal extent of this region as small as possible, particularly as far as the near layers of tape are concerned. Severe losses may occur when the recording region

[9] R. F. Dubbe, "Magnetic tape recording with longitudinal or transverse oxide orientation," IRE TRANS. ON AUDIO, vol. AU-7, pp. 76–79; May–June, 1959.

[10] We shall be interested in forms of erasure that occur during recording. Intentional erasure by means of a perpendicularly applied *external* field is, of course, inhibited by severe demagnetization, and is consequently relatively inefficient.

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extends over a distance comparable to the wavelength of the signal to be recorded.

Now, one of the conclusions of the previous section was that the critical bias range is substantially independent of field direction. Consequently, recording should take place in the region where the resultant bias field strength falls from H_2 to H_1. Such regions can readily be determined from a contour plot of the type shown in Fig. 3. For example, if we assume a gap length twice the coating thickness, and set the bias curent to a value which gives a gap field equal to H_2, recording takes place between the contour lines labeled 1 and $\frac{3}{4}$ in Fig. 3; the recording zone is then as shown by the shaded area (1) in Fig. 6(a). This would give quite good registration of short wavelengths, but would leave a large part of the coating underbiased, resulting in severe distortion at long wavelengths. If the bias current were doubled, the recording zone would lie between the contour lines marked $\frac{1}{2}$ and $\frac{3}{8}$, and would shift to the shaded area labeled (2) in Fig. 6(a). Similarly, a further doubling of bias current would shift the recording zone to the shaded area (3); the whole coating would now be overbiased with loss of sensitivity at long wavelehgths and very poor resolution at short wavelengths. The condition of cptimum long wavelength registration corresponds approximately to setting the bias current so that the farthest layer of the coating just receives the bias field amplitude H_2. This condition is more or less satisfied by recording in zone (2) of Fig. 6(a). A somewhat lower value of bias would be needed to achieve a reasonable compromise between the two desired requirements of long wavelength linearity and good short wavelength resolution.

The situation using a small record gap, equal to two fifths of the coating thickness, is depicted in Fig. 6(b).

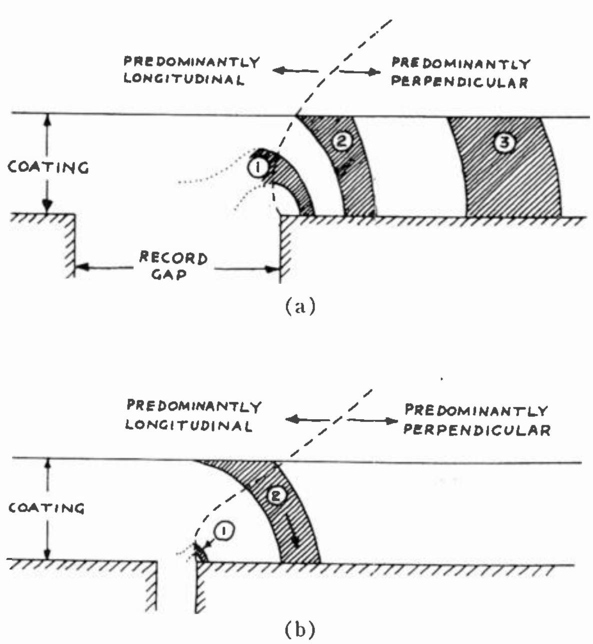

Fig. 6—Recording zones. (a) Large gap. (b) Narrow gap.

When the bias current is set to suitably small value corresponding to zone (1), resolution in the near layers is greatly improved, but the effective field extends into only about the first one-tenth of the coating, and the major part of the coating is grossly underbiased. In order to obtain satisfactory long wavelength recording, the bias must be increased so that the recording zone moves to position (2). Under this condition, the short wavelength resolution would, if anything, be worse than that obtained using the optimally biased long gap [Fig. 6(a), zone (2)].

To summarize, it is impossible in a conventional system to obtain optimum short and long wavelength recording at the same time. The best that can be done is to choose those values of the ratio of gap length to coating thickness and the bias current that give the best compromise over the range of wavelengths of interest.

A further point is that under all the conditions depicted in Fig. 6, recording takes place in zones where the field is predominantly perpendicular rather than longitudinal. Actually, the field will not turn very much past 45° but, even so, it is clear from the anhysteretic curves of Fig. 5 that full advantage is not taken of the high sensitivity in the direction of particle orientation. What may happen is that an efficiently recorded longitudinal signal may, crudely speaking, be erased by a subsequent rotation of the bias field towards the perpendicular direction without adding any appreciable perpendicular component of recorded magnetization.

Improved Recording Methods

Possible Techniques

At first sight, there are three approaches, any one of which may lead to a considerable improvement in the short-wavelength recording performance. The first and perhaps most obvious technique is to "sharpen" the field in the zone of recording. In this case, both the bias and signal decay equally as the element of tape leaves the recording area. The second approach is to reduce the bias separately from the signal and to reduce it first. That is, the bias must be reduced to a value below which it can no longer influence recording, while the signal strength remains at, or near, its maximum value. This would eliminate the over-biasing problem entirely, and would, therefore, provide a system wherein the same bias current setting would be uncritical and equally good for all wavelengths. The third approach is to produce a more uniform bias throughout the thickness of the oxide. If this could be accomplished, a given bias setting would be equally good for any point within the depth of the oxide. Short wavelengths, which are recorded at the surface, would not be over-biased.

Unfortunately, these ideas are very difficult to put into practice. Reducing the length of the trailing pole of the record head has been suggested as a means of sharpening the field. This can, however, have only a

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relatively small effect, for the record flux will by no means limit itself to the shortened pole surface, but will spread round it to enter other parts of the pole. Westmijze[11] has proposed limiting this "spread" by eddy-current shielding which, since the shielding would be most effective at the higher bias frequency, puts this proposal into the second category. The problem here is that it is extremely difficult to engineer a head of this type with the small dimensions of pole and conducting shield demanded by a practical system. As far as improving field uniformity is concerned, extending the head structure to the other side of the tape is an obvious technique, although one which is unattractive from an operational point of view. Three pole heads of this type have been suggested by Camras[12] but the optimal dimensions, magnetic potentials and disposition of the poles are critical and difficult to determine.

There is, however, a fourth approach to resolving the long-wavelength linearity vs short-wavelength response dilemma which is essentially very simple. That is to record the long- and short-wavelength parts of the signal sequentially, using heads of different gap lengths. This technique is discussed in detail below.

Multigap Recording

First, the relatively long-wavelength information is recorded by a head having a relatively large gap, capable of producing a uniform bias and signal field throughout the oxide and hence a good low-frequency performance. At some later time, the short-wavelength information is recorded, using a very small gap, in which the bias is adjusted to a low value for optimum recording of very short wavelengths. Because the field drops off very rapidly with distance away from the head surface, and because the bias is adjusted to a low value for optimum recording of short wavelengths, only a very small portion of the long-wavelength information is erased during this second recording. The fields in the two heads are illustrated in Fig. 7. It would be possible to use the same head, or heads with the same gap dimension, but with the bias adjusted to different values for the long-wavelength and short-wavelength recordings. This method would provide a considerable improvement over the ordinary method, but would not be as effective as having gaps of different sizes.

If no correlation were required between the short-wavelength and the long-wavelength information to be recorded, we could record these two signals at entirely different times and places. For most applications, however, the long and short wavelengths are parts of a complex signal and must, therefore, be recorded in synchronism with each other. This problem may be handled in several different ways. Either the distance between the points at which the two recordings are made must be very small, so that the delay is negligible for the particular type of recording being made; or a compensating delay must be introduced in the high-frequency portion of the signal to be recorded by the second head. The first may be accomplished either by placing two record heads extremely close together, or better still, by constructing a single head which has two gaps and in which sufficient isolation between the two gaps is obtained. Such a head is shown in Fig. 8. It is possible to achieve good isolation with this type of head, although interconnected windings may be necessary at various locations on all three legs.

A compensating delay may be provided by various means; ultrasonic delay lines are available, with delays up to quite a number of milliseconds, which might be usable for this application. Another form of delay is the use of a drum recorder, where the information is recorded at one point and picked off any desired degree of rotation later on. For the making of duplicate tapes, a very simple technique may be used to provide the required delay; that is, two separate reproduce heads may be placed on the machine on which the master is being played. The first reproduce head would be used to provide the low-frequency information for the first record head, and the second reproduce head would provide the high-frequency, short-wavelength signal for the second record head. The reproduce heads would, or could be, identical and would merely be fed into separate reproduce amplifiers, filters, and record amplifiers.

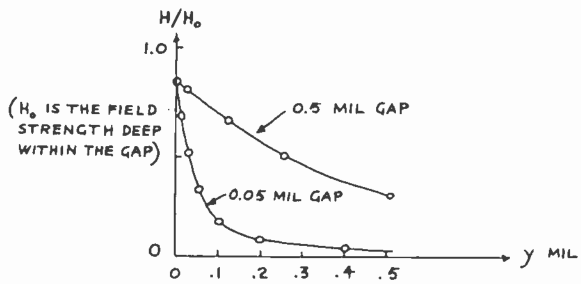

Fig. 7—Fields at gap centerplane from heads with broad and narrow gaps.

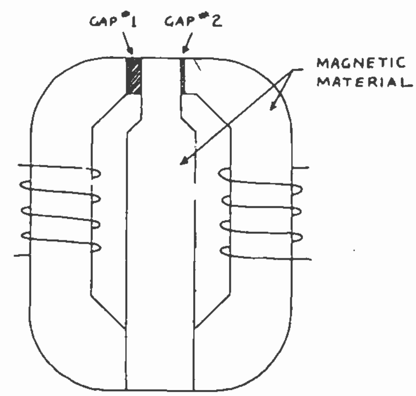

Fig. 8—Two-gap record head.

[11] W. K. Westmijze, U. S. Patent No. 2,854,524; 1952.

[12] M. Camras, *Armour Res. Foundation Bull.*, no. 73; (September, 1951).

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With any method of delay it will generally be desirable to pass the low- and high-frequency portions of the signal through separate low-pass and high-pass filters respectively. Since the bias on the second head is adjusted optimally for the recording of very short wavelengths, any long wavelengths recorded by this head would be distorted to some degree. The over-all response contributed by the two portions of the system is shown in Fig. 9(b) and (c). The over-all output will simply be the sum of these two transfer characteristics. It is obvious that there will be some interference between the signals at the cross-over point. If the two are out of phase, there will be some degree of cancellation; and if they are in phase, there will be addition. This may be analyzed as follows:

Let the double-gap recording system have the characteristics illustrated diagrammatically in Fig. 9; Fig. 9(a) indicates the way in which recording takes place at the two gaps. The separation d between the two recording zones leads to a time difference $T=d/v$ between the recorded signals. Fig. 9(b) shows the response-frequency characteristics of the long-gap recording channel, including the effect of the bias from the short gap plus low-pass filtering and replay equalization. The transfer function of this essentially low-pass characteristic is represented by

$$A = Kg(f),$$

where $g(f)$ is a decreasing function of f of initial value $g(0)=1$. Fig. 9(c) shows the corresponding characteristic of the short-gap recording replay channel. If the response characteristic of the double-gap system as a whole is to be flat, the transfer function of the short-gap channel is give by

$$B = K[1 - g(f)].$$

Recording with both gaps simultaneously, we get an output proportional to

$$A \sin wt + B \sin w(t - T) = \sin wt(A + B \cos wT) - \cos wt(B \sin wT),$$

so that the transfer function of the combined channels is given by C, where

$$\begin{aligned} C^2 &= (A + B \cos wT)^2 + B^2 \sin^2 wT \\ &= A^2 + B^2 + 2AB \cos wT \\ &= (A + B)^2 - 2AB \sin^2 (wT/2) \\ &= K^2[1 - 2g(f)[1 - g(f)] \sin^2 fT], \end{aligned}$$

or the normalized transfer function is given by

$$C/K = [1 - 2g(f)[1 - g(f)] \sin^2 fT]^{1/2}.$$

Minima in the response will therefore occur when

$$\pi fT = \pi/2, \quad 3\pi/2, \quad 5\pi/2, \cdots (2n + 1)\pi/2,$$

i.e., at frequencies given by

$$f_0 = 1/2T, \quad f_1 = 3f_0/2, \quad f_2 = 5f_0/2, \quad f_n = (2n + 1)f_0/2,$$

and the ratio of the output of the nth minimum to the maximum output will be given by

$$(1 - 2g(f_n)[1 - g(f_n)])^{1/2},$$

and has its least value of $\frac{1}{4}$, or -12 db, when $g(f_n) = \frac{1}{2}$, that is to say, at the cross-over frequency f_c.

Typical values for a practical system are:

$$d = 6 \text{ mil}$$
$$v = 1.85 \text{ ips}$$
$$T = 3.2 \text{ msec}$$
$$f_0 = 156 \text{ cps}.$$

Minima will therefore be spaced 156 cps apart in the region of the cross-over frequency (normally about 1.5 kc) and have a maximum possible depth of 12 db. How many significant minima there are, and how nearly the worst one approaches a depth of 12 db, will depend upon the sharpness of the filtering and the choice of the cross-over frequency. Ideally, if the cross-over frequency is adjusted to be an integral number

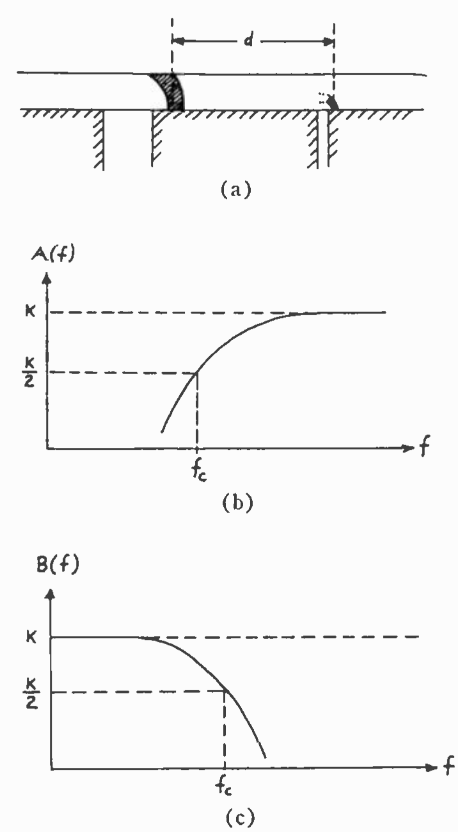

Fig. 9—Illustration of two-gap record process (a) Recording zones. (b) High-pass characteristic (short-gap channel). (c) Low-pass characteristic (long-gap channel).

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of f_0's, and the filters effectively cut off within a frequency range $f_0/2$, there will be no minima. This argument, of course, ignores any of the miscellaneous phase shifts which must inevitably exist in the two channels, and in practice the required filter adjustments will tend to be critical.

A preliminary experimental verification of the multigap technique was obtained at $1\frac{7}{8}$ ips with the results shown in Fig. 10(a) and (b). Long-wavelength recordings were made, using an ordinary head having a 0.5 mil gap with the bias adjusted to obtain maximum output at 125 cps (14 db below saturation level). Short-wavelength recordings were made using a head having a 0.1-mil gap with the bias adjusted for maximum output at 10 kc. In each case the record current was adjusted to give an output 14 db below saturation at the frequency used for setting the bias, and this current was used throughout the subsequent tests. The partial erasure of the long-wavelength recordings by passing them over the 0.1-mil gap, energized by bias alone, is shown in Fig. 10(a). The erasure is less than 2 db for frequencies below the probable cross-over frequency of approximately 2 kc. The frequency response of the 0.1-mil gap recording is plotted relative to the response of the 0.5-mil gap recording in Fig. 10(b). It seems from the curve that the potential improvement to be gained from a double-gap technique incorporating the above gap dimensions and bias conditions is approximately 12 db/octave. Extrapolation to 15 kc indicates an improvement of some 36 db relative to the admittedly somewhat over-biased 0.5-mil gap recording.

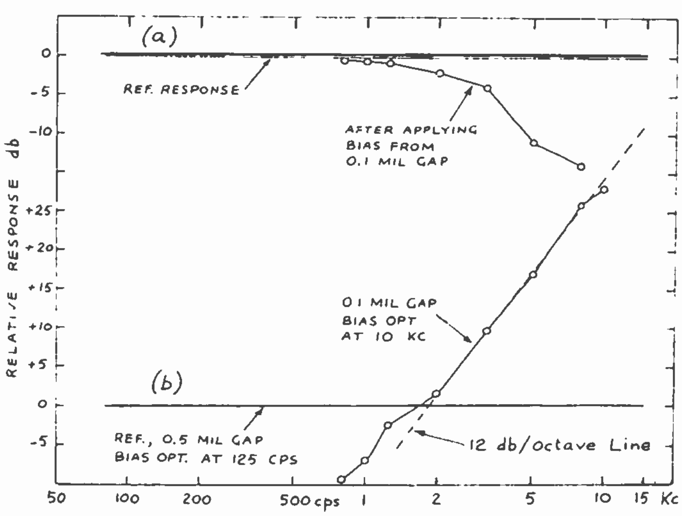

Fig. 10—Response-frequency curves. (a) Partial erasure of 0.5 mil gap recording by 0.1 mil gap bias. (b) Comparison of short gap and long gap response.

Conclusions

The multigap recording technique has proved to be effective in overcoming the frequency-response limitations of conventional ac-biased recording. In fact, this technique, or a modified form of it, may well prove to be the best for many applications. It is certainly the simplest. Initial tests showed that the potential gain in 15-kc response at $1\frac{7}{8}$ ips was more than 30 db using conventional tape; these results have been confirmed in later and more practical forms of the device. Time delay compensation is not too serious a problem provided duplication—rather than direct—recording is involved, because correction can be introduced by reproducing the master tape using two suitably spaced gaps. Flutter requirements may be critical when compensating for long-time delays but should be within the range presently achieved on high-quality tape transports.

It is probable that a further major improvement must await the production of more suitable tapes. Use of the multigap recording technique enables the audio-frequency range to be covered adequately at $1\frac{7}{8}$ ips, but the background noise after equalization is relatively high. A better tape would have a lower noise level in the presence of bias, or require less equalization, or would incorporate both these qualities.

Finally, it should be mentioned that the use of the multigap recording method need not be confined to low-speed audio recording. It could be used to improve the performance of higher-speed, audio-frequency recording systems and also analog systems going to higher frequencies. In particular, it could very easily be used to increase the number of channels in a telemetry data recorder. The problem of time-delay compensation need not arise in the latter case, if the channels are suitably divided between the heads (or gaps).

Added Note

Since the original preparation of this paper in 1959, it has come to the authors' attention that other laboratories have worked on the multiple-gap recording system more or less simultaneously. Work done by Woodward at RCA was described in a paper presented at the Audio Engineering Society Meeting in October 1961. Work done in the Philips Laboratories, Eindhoven Netherlands, will be described in a paper to be presented at the Acoustical Congress in Copenhagen in August, 1962, written by Teer, de Niet and Tjaden. Also, a U. S. patent was issued to Derk Kleis of Philips in December, 1961, which describes a dual-gap recording system.

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Fabrication of a Magnetic-Tape Transducer by Electroplating and Engraving*

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Summary—**A new technique for the construction of magnetic-tape heads is described. In this technique the magnetic material in the vicinity of the air gap is deposited by electroplating and the air gap is formed by engraving. Analysis of the leakage flux and of the pole piece saturation is presented. The performance of the head is evaluated in terms of frequency response.**

INTRODUCTION

THE PERFORMANCE of most magnetic-tape devices is influenced greatly by the mechanical tolerances which can be maintained in the manufacture of the heads. In all types of recording it is imperative that the recording and playback gaps be parallel. Also, in many important applications, a number of tracks are recorded simultaneously.[1] In this case, the recording and playback gaps must be parallel, and the spacing between them must be the same for all tracks, in order to maintain the time relation between the tracks. These tight requirements exist in the manufacture of digital recording machines, scientific analog recording machines, and stereo recording machines for entertainment purposes. These tolerances are difficult to meet by conventional manufacturing processes.

The purpose of the novel head fabrication technique described here is to simplify the meeting of these dimensional tolerances. The main feature of this new head is that the usual precision grinding and assembly operations are replaced by a simple engraving operation. This is the type of engraving used in the manufacture of microscope reticles. It is possible to form the air gap in this head by engraving because the magnetic material in the vicinity of the air gap is a very thin electroplated deposit.[2]

In addition to describing the method of manufacture, this paper will be primarily concerned with the magnetic design of the head. The maximum recording flux density in the head is calculated considering the leakage flux and head dimensions. From the results of this calculation it is possible to choose the head dimensions to attain a value for the peak flux density which is less than the saturation flux density of the head material. In a second calculation the playback leakage flux is determined in terms of the permeability and head dimensions. On the basis of these results it is possible to obtain efficient utilization of the playback flux.

In the design of the conventional-type ring head these magnetic considerations are usually of secondary importance because the mechanical strength requirements lead to a structure which is more than adequate from the magnetic standpoint. However, in the electroplated head the magnetic and structural functions are separated.

The essential parts of a magnetic tape head are a magnetic path containing a small air gap and a signal coil linking this path. Frequently this device is made in the form of a ring as shown in Fig. 1. For recording, the signal current is applied to the signal coil producing an intense magnetic field outside the ring at the air gap. The magnetic tape is drawn past this air gap and assumes a permanent magnetization more or less proportional to the magnetic field at the air gap. As the recorded tape is again drawn past the head, flux, which is proportional to the intensity of magnetization of the tape, is induced in the head and generates a voltage in the signal coil.

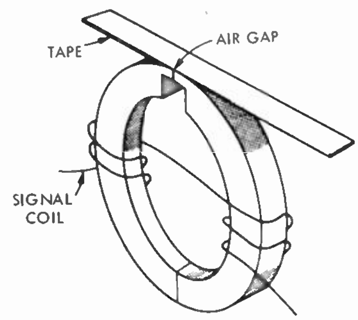

Fig. 1—Conventional magnetic-tape head.

Magnetic-tape heads are usually constructed in two pieces. The abutting surfaces of these halves are ground and polished so that a minimum air gap occurs when the two halves are put together. During actual assembly of the head a thin nonmagnetic shim is placed in the air gap to control its dimension. After assembly the pole pieces are faced off to present a smooth surface to the tape.

A schematic of the electroplated head is shown in Fig. 2. In this figure the supporting structure is suggested by the dotted lines. The unique feature about the electroplated head is that the magnetic material

* Received April 10, 1962.
† Applied Research Laboratory, Sylvania Electronic Systems, Waltham, Mass.
[1] P. C. Goldmark, C. D. Mee, J. D. Goodell, and W. P. Guckenburg, "A $1\frac{7}{8}$-ips magnetic recording system for stereophonic music," IRE TRANS. ON AUDIO, vol. AU-8, pp. 161–167; September–October, 1960.
[2] I. W. Wolf and V. P. McConnel, "Nickel-iron alloy electrodeposits for magnetic shielding," *Proc. Am. Electroplaters' Soc.*, vol. 43, pp. 215–218; 1956.

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in the immediate vicinity of the air gap is formed by electroplating and the gap itself is formed by engraving. At some distance from the air gap, the electroplated material is attached to a magnetic member, made from sheet stock, which completes the magnetic path around the air gap. If the head is intended for low-frequency applications the electroplating can be made quite thick without eddy current problems. In this case a major portion, or perhaps all of the magnetic path, can be made by electroplating. However, for high-frequency applications, eddy currents limit the effective thickness of the magnetic material. Since it is not practicable to laminate electroplated material it is necessary to limit the length of the electroplated path.

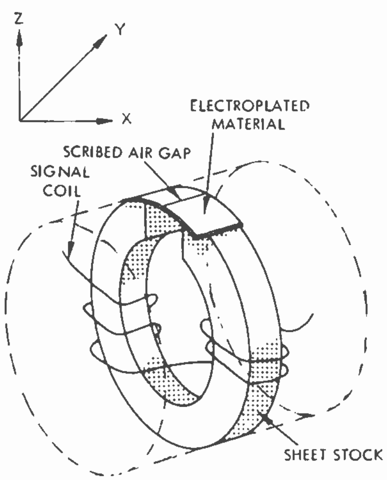

Fig. 2—Electroplated head.

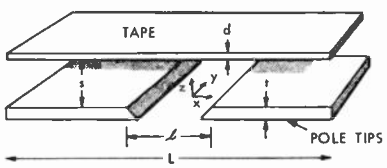

Fig. 3—Electroplated head pole tips.

Design of the Electroplated Head

General

In the following discussions the coordinate system defined in Fig. 3 is used. The curved surface of the pole pieces is developed into a plane parallel to the x axis.

The over-all performance of a magnetic-tape transducer is determined by the gap length, l. Depending upon the desired frequency response, the gap length is chosen between 0.1 and 1 mil (10^{-3} inches). The lower limit on the gap length can be obtained with this method of fabrication of the head, only by mechanically cutting out the gap using a sharp pointed diamond tool. This is a standard engraving process. When the gap is formed by scribing, the shoulders are sharp and well defined. The cutting point on the diamond has an included angle between 45° and 90°. (The angle can be specified within these limits.) The width of the cut at the top surface is consequently between 0.8 and 2 times the depth of the cut. Since the air gap must penetrate completely through the magnetic material, this means that the minimum air gap length, l, is approximately equal to the thickness of the magnetic material at the pole tips.

Very small air gaps are possible. Air gaps one micron wide have been routinely scribed in thin magnetic films deposited on glass.

Because the magnetic material on either side of the air gap cannot be much thicker than the width of the air gap, these pole pieces are ordinarily very thin. This thin cross section can only conduct the signal flux efficiently for a short distance. In order to reduce the leakage flux and the reluctance of the head the cross section is increased close to the scribed area. In conventional heads the body of the head is similarly shaped in the immediate vicinity of the air gap. (Compare Figs. 1 and 2.)

There are two things to be considered in the design of the magnetic members in the heads: 1) the cross-sectional area must be large enough to permit operation significantly below the saturation level; 2) the leakage flux, particularly on the playback operation, should be small compared to the signal flux. We shall investigate each of these considerations and base our design on the most limiting of them.

Pole Tip Flux

Saturation of any portion of the transducer will drastically degrade its performance. This situation is most likely to occur during recording and so this case will be considered here. It is not particularly difficult to make the portion of the head fabricated from sheet stock of sufficient cross-sectional area to avoid any possibility of magnetic saturation. However, since the cross-sectional area of the electroplated pole tips is so intimately connected with the desired air gap width, and hence with the desired frequency response, detailed analysis of this portion is justified to insure that magnetic saturation of the pole tips does not occur.

Assuming that the pole tips are constant in cross-sectional area, the peak flux density will occur at the root of the pole tip where the electroplating attaches to the rest of the head. We will calculate the flux density in the pole tip at the root as a function of the pole tip length.

The finite permeability of the pole piece is of only secondary importance in this case because the flux between the pole pieces is concentrated in the immediate area of the air gap. Thus, the assumption that the pole pieces are equipotentials is appropriate. If the electroplating is supported on a massive conductor, the con-

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ductor will serve as a magnetic insulator at the higher frequencies, reducing the amount of flux leaving the electroplating on the conductor side. To be conservative in the following calculations this effect will be neglected.

For analysis purposes it will be assumed that the head is infinite in extent in the y direction. The pole pieces will be developed out to lie in the x-y plane and the thickness in the z direction will be neglected. The air gap will be centered about the origin. In both record and playback operation a considerable magnetic potential exists across this air gap. (See Fig. 3.)

Using these assumptions, the field intensity outside the pole piece is

$$H = \frac{I}{\pi r} \quad \text{where} \quad r = (x^2 + z^2)^{1/2}. \tag{1}$$

Let H_0 be the magnitude of the recording field which is to exist at $r = l/2$. Then from (1)

$$H = \frac{lH_0}{2r} \tag{2}$$

and the total flux leaving both sides of the pole tip is

$$\Phi = \mu_0 b H_0 \log \frac{L}{l} \cdot \tag{3}$$

Note: All logarithms are to the base e.

Remembering the consideration described earlier, that the thickness of the electroplating must be approximately equal to the length of the air gap, the flux density in the pole tips is

$$B = \frac{\Phi}{bC} = \mu_0 H_0 \log \frac{L}{C} \cdot \tag{4}$$

Rearranging (4) into a form most convenient for design gives

$$\frac{L}{C} = e^{B/\mu_0 H_0}.$$

This equation gives the maximum ratio of pole piece length to pole piece thickness in terms of the peak flux density in the pole piece and the recording field.

Assuming that $\mu_0 H_0 = 10^3$ gauss; and $B = 5 \times 10^3$ gauss, we get

$$\frac{L}{C} = 148 \ . \tag{5}$$

Leakage

Not all the flux which is intercepted by the pole pieces in playback is conducted through the signal coil. A portion of the signal flux escapes from the pole pieces by-passing the signal coil. This leakage flux is not effective in producing an output signal. In the following analysis a relationship between the leakage flux and the pole piece dimensions will be obtained.

In the previous analysis we assumed that the two pole pieces were equipotentials. This naturally leads to a magnetic field normal to their surface which is inversely proportional to the distance from the air gap and proportional to the magnetic potential between the two pole pieces. This is contained in (1). For this analysis of leakage, we wish to account for the fact that the pole pieces are not exactly equipotentials. However, since they are almost equipotentials it seems reasonable to assume that the flux density emerging from the surface at a particular point is proportional to the magnetic potential of the point and inversely proportional to the distance of the point from the origin.

Because the sheet stock portion of the transducer is large in cross-sectional area the leakage from it is small. Hence we will consider only the leakage from the electroplated pole pieces.

The continuity principle then leads to the following equation for the flux in the pole pieces:

$$\frac{d^2\Omega}{dx^2} = \frac{\Omega\eta^2}{x} \tag{6}$$

where

$\eta^2 = +4/\pi C\mu$
C = thickness of the pole piece
μ = permeability
Ω = magnetic potential.

The boundary conditions are that a flux Φ_0 is inserted into the pole tip at $x = l/2$ and the other end of the pole tip at $L/2$ is held at zero magnetic potential. A portion of the flux which is put into the pole tip will flow to the other end. This portion is effective in producing a signal voltage. The rest of the flux will leave the pole tip and travel in a generally semicircular path to the other pole tip.

The solution of (6) is of the general form

$$\Omega = \sqrt{x}\left[C_1 J_1(2j\eta x^{1/2}) + C_2 Y_1(2j\eta x^{1/2})\right]. \tag{7}$$

For the boundary conditions:

$$\frac{d\Omega}{dx} = -\frac{\Phi_0}{A\mu\mu_0}, \qquad \text{at } x = \frac{l}{2}$$

and

$$\Omega = 0, \qquad \text{at } x = \frac{L}{2}$$

the relative flux which reaches the point $x = L/2$ is

$$\frac{\Phi}{\Phi_0} = -\frac{J_0(\alpha)H_1{}^1(\alpha) - J_1(\alpha)H_0{}^1(\alpha)}{J_1(\alpha)H_0{}^1(\gamma) - J_0(\gamma)H_1{}^1(\alpha)} \tag{8}$$

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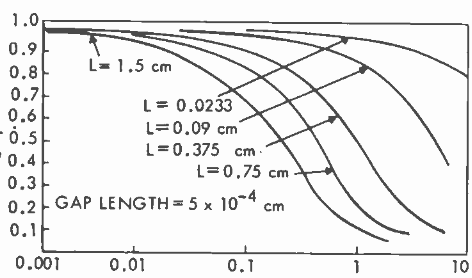
where

$\gamma = 2j\eta(l/2)^{1/2}$
$\alpha = 2j\eta(L/2^{1/2}$
Φ_0 = flux which reaches $x = L/2$ when $\mu = \infty$
A = cross-sectional area of the pole tip
l = air gap length
L = pole piece length.

Eq. (8) is plotted in Fig. 4 for several different lengths of the pole piece. A value of 5×10^{-4} cm has been used for the air gap length in calculating these curves.[3] Taking a reasonable number for the permeability, $\mu = 1000$, the length of the pole piece can be plotted vs the thickness. (See Fig. 5.) It is clear from this figure that if the air gap is to be small, for example, less than 0.5 mil and hence the thickness of the electroplating is to be less than 0.5 mil, then the length, L, of the electroplating should be less than 0.05 inch to obtain $\Phi/\Phi_0 > 0.9$.

For wear and dimensional tolerance reasons it is worthwhile to be conservative in the choice of L and C.



$$\eta^2 = \frac{4}{\pi C\eta} \text{ (centimeters)}^{-1}$$

Fig. 4—Fraction ϕ/ϕ_0 of the intercepted playback flux which reaches the signal coil as a function of the parameter η^2 and the length of the pole piece.

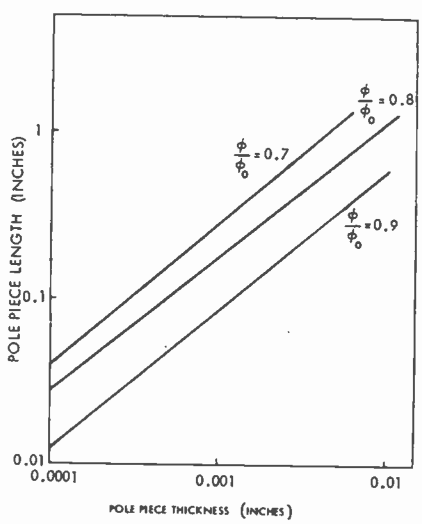


Fig. 5—The fraction ϕ/ϕ_0 of playback flux which is delivered to the signal coil as a function of the pole piece length and thickness. Plotted for $\mu = 1000$, $l = 5\times10^{-4}$ cm.

[3] These results are not sensitive to the air gap dimension.

Eddy Current Effects

In general, the design of the magnetic structure of the head is described in terms of the permeability and thickness of electroplating. The general goal is to make the thickness C, and permeability μ, as high as possible.

Eddy current effects can be considered to modify the effective values of C or μ. It appears that, for this case, it is most convenient to express the eddy current effects in terms of skin depth. The skin depth in this particular situation is

$$\delta = \frac{1}{[\omega\sigma\mu\mu_0]^{1/2}}.$$

Typical values for the conductivity and permeability of electroplated material are

$\sigma = 6.6\times10^6$ mho/meter
$\mu = 2000$

so that

$$\delta = \frac{0.01}{\sqrt{F}} \text{ cm} \quad (9)$$

for F in kilocycles.

The skin depth, δ, is the maximum effective thickness of C, which can be obtained. Substituting this maximum value for C and a typical value for the permeability into the expression for η, an expression in terms of frequency for the minimum obtainable value of η is obtained:

$$\eta^2 = 0.0636\sqrt{f} \text{ cm}, \quad (10)$$

where f is in kilocycles. Thus, at a frequency of 100 kc, the minimum value for η^2 that can be obtained with typical materials is $\eta^2 = 0.636$ cm. Correspondingly the maximum effective thickness is $C = 0.001$ cm. Referring to Fig. 5 this means that for $\Phi/\Phi_0 = 0.9$ in playback the over-all pole piece length should be less than 0.04 inch. Also, to prevent saturation during recording, the pole piece length should be less than 0.059 inch.

Performance

The primary evaluation of the performance of the electroplated head is in terms of its frequency response. The measured frequency response of an electroplated head is shown in Fig. 6. This response is in excellent agreement with the calculated frequency response. This agreement is particularly marked for the position of the first null in the frequency response. For a magnetic-tape head with thin pole pieces the expected frequency response is given by[4]

$$e = NM_0bv(1 - e^{-2\pi d/\lambda})e^{-2\pi S/\lambda}J_0\left(\frac{\pi l}{\lambda}\right)\int_0^{\pi L/\lambda} J_0(\zeta)d\zeta$$

[4] This equation adapted from W. K. Westmijze, "Studies on magnetic recording," *Philips Res. Repts.*, vol. 8, pp. 148–157, 161–183, 245–269, 343–366; April, June, August, October, 1953.

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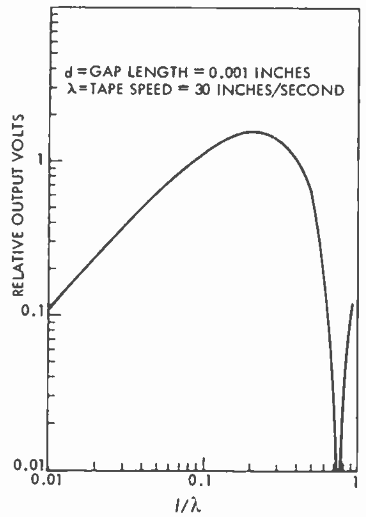

Fig. 6—Measured relative output of electroplated head.

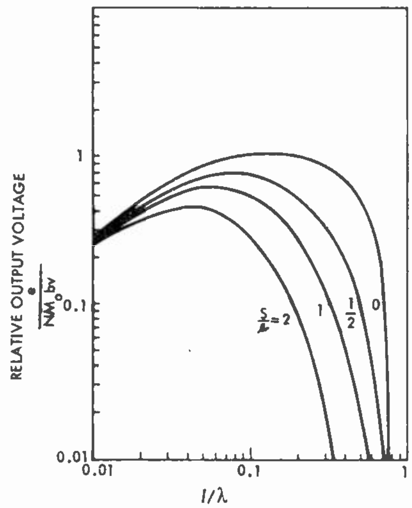

Fig. 7—Calculated relative head output as a function of normalized frequency.

where

b = track width
M = peak magnetization
N = number of turns on signal coil
V = tape velocity
d = thickness magnetic coating
λ = wavelength of recorded signal
S = tape-to-head spacing
l = head air gap length
L = length of head coupled to the tape.

This equation differs from the usual expression in that the Bessel function replaces the sine function. The first null for the Bessel function appears at $l/\lambda = 0.76$ and for the sine function $l/\lambda = 1$. The frequency response predicted by this equation is plotted for several values of tape-to-head separation in Fig. 7.

A number of curves are given in this figure to show the effect of spacing the tape away from the head a distance S. As this spacing increases, the frequency decreases at which the maximum output from the head is obtained. In general, the effect of spacing the head away from the tape is a most pronounced decrease in the output at the higher frequencies. Because of this, a very high price in terms of bandwidth is paid for increasing the head life by overcoating the head or tape with a protective layer.

Conclusions

A technique of magnetic head construction has been described in which the precision machining has been confined to the comparatively simple scribing operation. Precise alignment of the gaps in a multitrack head is easily accomplished. Indeed, alignment of record and playback heads is also easily accomplished by mounting the recording and playback heads on a common foundation before scribing the air gaps. The electroplated head can be operated in the fractional megacycle range, this method of forming the air gap having no degrading effects on the frequency response. Because of the tight connection between the gap width and the magnetic material thickness, there are definite limitations on the useful life of the head.

For the slow tape speed entertainment applications and for the applications where the head does not touch the record, such as the disk and drum digital storage devices, wear presents no problem.

Acknowledgment

The actual physical design of the several different heads used in this project was performed by G. Ratcliffe and the electroplating work was done by K. Lang. D. Meyers collected the performance data.

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Some Experiments with Magnetic Playback Using Hall-Effect Sensitive Elements*

MARVIN CAMRAS†, FELLOW, IRE

Summary—**Flux sensitive heads using thin semiconductors have been developed for playback of magnetic recordings. The elements have a frequency response inherently flat from dc to tens of megacycles, so that the main limitations are in the associated head structure. Factors entering into optimum design are discussed, including materials and configurations of semiconductor elements and cores. Experimental results for successful designs are given, and a number of applications are suggested.**

PICKUP HEADS commonly used for playback of magnetic recordings are sensitive only to rate of change of flux picked up from the tape, and hence have an important basic characteristic: that as the frequency decreases the output falls off in proportion, becoming zero at zero frequency.

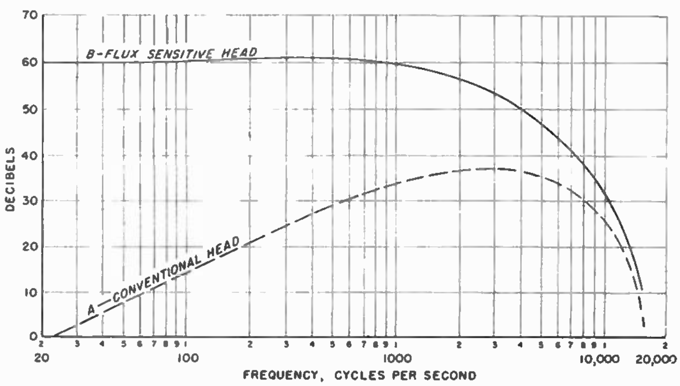

Fig. 1—Unequalized frequency response of two types of heads when playing back the same constant-current recording.

This results in the familiar constant-current response curve of Fig. 1-A. To compensate for the drop at low frequencies, the amplifiers used with standard playback heads require a bass-boost amounting to 30 or 40 db at 30 cycles. As the frequency is decreased still further a point is reached where the head output is too low to be useful, and some other method must be found for sensing the recording on the tape.

One application which requires a very low frequency response is where data is recorded on tape at normal speeds and played back very slowly for analysis.[1] Another application is where control or reference pulses are recorded which must be picked up and counted at different and variable speeds even when the record slows down, stops, and starts again.

A number of approaches have been suggested for pickups that would be sensitive to magnetic flux rather than its rate-of-change.[2] These have an inherently flat response down to zero frequency as in Fig. 1-B. One class of flux sensitive detectors is based on the idea of interrupting or modulating the flux from the record at a fairly high rate, thus giving a rate-of-change of flux which can be sensed with a coil. Motor driven vanes and vibrating reeds in the head core were proposed, but the result can be achieved more simply by the magnetic modulator principle, where the signal flux is modulated by means of auxiliary windings on a saturable portion of the head.

Another class of detectors utilizes magnetoelectric effects other than electromagnetic induction, including magnetoresistance, Hall effect, the deflection of electron beams,[3] and the (slight) sensitivity of transistors to a magnetic field.

Still other miscellaneous magnetic effects are available, such as rotation of polarized light beams,[4] magnetomechanical forces, and changes in incremental permeability.

Of all the above, the magnetic modulator principle has probably been the most successful. However it does have some limitations: a source of high-frequency excitation is required; there is background noise due to the Barkhausen effect; an upper limit to the frequency response is inherent in the ferromagnetic core structure; and windings are still required as in conventional heads.

Hall effect sensitive elements do not have the above limitations (although they have a few of their own, as will become apparent). The possibility of low manufacturing cost and the inherently flat playback response makes it conceivable that such heads might replace conventional heads, which up to the present have not had

* Received March 23, 1962. To be published in the 1962 IRE International Convention Record.

† Armour Research Foundation of Illinois Institute of Technology, Chicago, Ill.

[1] M. Camras, "Tape recording applications," IRE Trans. on Audio, vol. AU-3, pp. 174–182; November–December, 1955. (See p. 178.)

[2] O. Kornei, "Survey of flux-responsive magnetic recording heads," *J. Acoust. Soc. Am.*, vol. 27, p. 575; May, 1955.

[3] A. M. Skellett, L. E. Leveridge, and J. W. Gratian, "Electron beam head for magnetic playback," *Electronics*, vol. 26, p. 168; October, 1953.

[4] A. W. Friend, "Magneto-optic transducers," *RCA Rev.*, vol. 11, p. 482; December, 1950.

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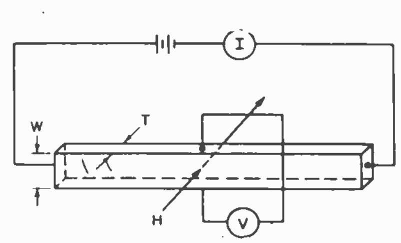
a competitor except for special and expensive instrumentation uses. Accordingly, Hall-element heads were investigated, both analytically and experimentally, to determine whether an advantageous design was possible.

The Hall Effect

The Hall effect is named after E. H. Hall, who discovered in 1879 that he could skew the equipotential lines in an electrical conductor by applying a magnetic field.



Hall voltage, $V_H = RIH/T$
I = current
H = magnetic field
T = thickness
R = Hall coefficient = $1/ne$
ρ = Resistivity = $1/neu$
$R/\rho = u$
u = 2000 for germanium
u = 30000 for InSb
n = number of carriers
e = charge per carrier
u = mobility of carriers

Fig. 2—The Hall effect.

The Hall effect is shown in Fig. 2. A conductor of width W and thickness T carries a current I. With no magnetic field, if a voltmeter V is connected to opposite edges on the same equipotential line it reads zero. When a magnetic field H is applied at right angles to both the current and to the voltage axes, the voltmeter gives a steady deflection. The magnitude of this Hall voltage is

$$V_H = \frac{RIH}{T}$$

where R is the Hall-coefficient characteristic of the material.

The above formula satisfies our intuitive expectations that the generated voltage should be proportional to field strength (H), to density of current (I/WT), and to separation (W) between the voltage pickup points.

Ordinary conductive materials have a Hall effect which is too small to be of value as a sensor for magnetic fields. But certain semiconductors have Hall coefficients which are orders of magnitude higher, and these have made it practical to sense fields of magnetic-tape recordings.

Playback Heads

A Hall-effect playback head may have the same core structure as a conventional head, but instead of the winding, a semiconductor element is placed where magnetic flux from the tape can act on it. Fig. 3 shows a Hall element in the back gap of a pair of C-shaped cores, with the front gap contacting the tape recording. There are four terminals. Two of these are energized by a steady dc current of perhaps 50 to 500 milliamperes. At the other two terminals, an output voltage appears which depends on magnetic flux from the tape that is picked up by the core. This is true even if the tape is not moving, in which case the output is dc of positive or of negative polarity depending on the direction of core flux. Fig. 4 is a photograph of an experimental head of this kind.

But a conventional core is not necessary, and in fact a coreless (as well as coilless) head is possible as in Fig. 5(a). Here a miniature semiconductor wafer is mounted so that one of the thin edges bears against the tape. The field of the tape acts directly on the element. In the absence of coils and cores the high-frequency response of this head is limited only by the Hall effect; and the Hall effect operates at frequencies as high as 10,000 Mc (10 Gc).[5] Ferromagnetic effects such as nonlinearity, hysteresis, and Barkhausen noise are absent.

While the elegance of a coreless design may have special appeal to mathematicians and to high-fidelity enthusiasts, omission of the core is detrimental to resolving power and to sensitivity of the head. If we do not need the full 10,000 Mc response (and we probably won't until the mechanical engineers give us faster tape-drives) then we can back up the element with ferrite pieces as in Fig. 5(b) and still go to about 100 Mc. Or we can use thin metal cores if the upper frequency limit does not exceed a few megacycles. For convenience, the above heads are designated as "front gap" heads.

Heads as in Fig. 5, where the element is next to the tape, have the problem of how to connect to the edge of the semiconductor on which the tape rides. Several methods of making this connection have been proposed. However, the construction and operation of the head is greatly facilitated if the connection is eliminated altogether. Three ways that we have tested are shown in Fig. 6. In Fig. 6(a) a phantom equipotential point is established by connecting one of the output leads to a tapped resistor in place of the missing side terminal. This arrangement loses about half the output voltage. Fig. 6(b) is a five-terminal element where the exciting current flows in opposite directions from the center to each end; hence the output terminals b and d can be at the same quiescent potential, but acquire opposite potentials when a magnetic field is present. Best results from the standpoints of output and low noise were obtained with a K-shaped element as in Fig. 6(c).

[5] D. P. Kanellakos, R. P. Schuck, and A. C. Todd, "Hall effect wattmeters," IRE Trans. on Audio, vol. AU-9, pp. 5–9; January-February, 1961. (See p. 8.)

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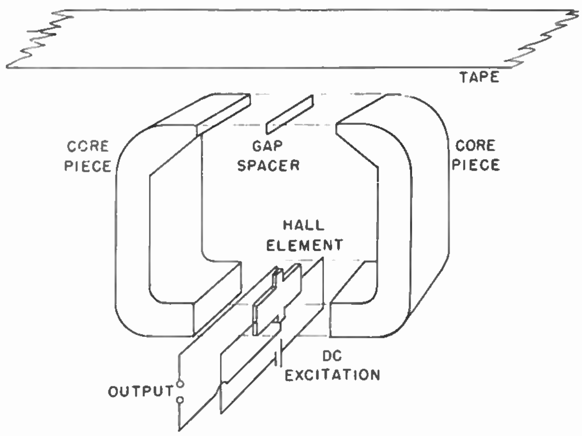


Fig. 3—Elements of a back-gap Hall-effect head.

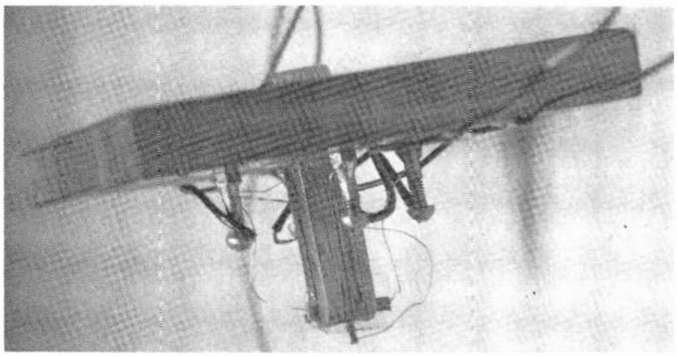
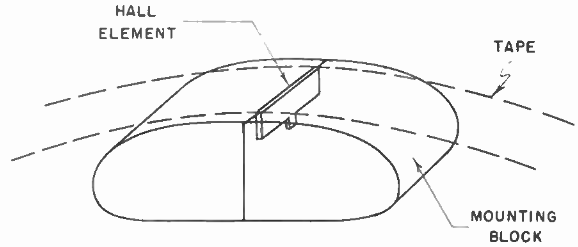
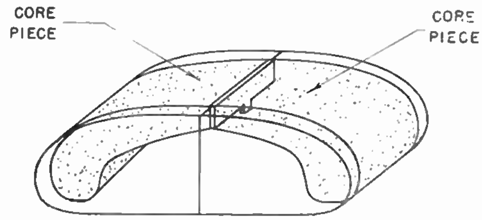


Fig. 4—Experimental head.

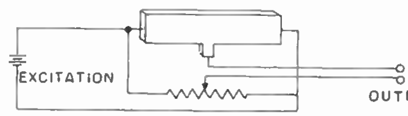


(a) Coreless.

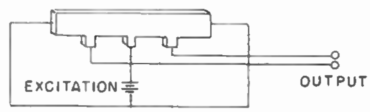


(b) With cores.

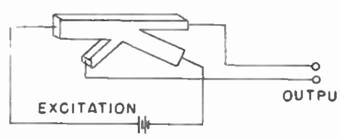
Fig. 5—Front-gap Hall-effect heads.



(a) Three-terminal with phantom equipotential.



(b) Four-terminal push-pull element.



(c) Four-terminal K-element.

Fig. 6—Circuits for use with front-gap heads.

Factors for Optimum Design

For playback heads we are interested in linearity, sensitivity, and a low noise level. The linearity is practically perfect up to the highest fields likely to be encountered in magnetic recording, as is shown by the experimental curve of Fig. 7 which is typical of Hall elements.

The sensitivity is determined by geometry of the head and element, and by the electromagnetic properties of the element. Referring again to Fig. 2 and to the equation for Hall voltage

$$V_H = \frac{RIH}{T}$$

it would appear that we should seek a material with the highest possible Hall coefficient (R). Experience indicates that this is not sufficient, because resistivity (ρ) of the material is also important in two ways: 1) lower resistivity gives less heating and allows the exciting current (I) to be increased; and 2) lower resistivity means that the output voltage can be delivered into a lower impedance load. A good index of electromagnetic merit is the mobility, which is the Hall coefficient divided by the resistivity.

$$\text{Mobility} = \mu = \frac{R}{\rho}.$$

Germanium has a mobility of approximately 2000, while the mobility of indium antimonide is approximately 30,000. Experience with heads using these semiconductors confirmed that indium antimonide was superior.

The exciting current (I) will normally be set at the highest safe value, since the output voltage goes up in proportion. A major limitation is the heat generated by ohmic losses in the exciting circuit. Semiconductor elements are temperature sensitive, and the output level will drift as the head warms up. The exciting current is therefore determined by temperature stability as well as by possibility of burnout.

The field (H) results from whatever tape flux can be channeled through the Hall element. A quarter-inch tape at saturation can supply about $\frac{1}{2}$ Maxwell; but at normal recorded wavelengths, intensities and track widths a realistic estimate would be 1 per cent to 10 per cent of this amount. Leakage and core losses reduce this still further, so that the element operates at very

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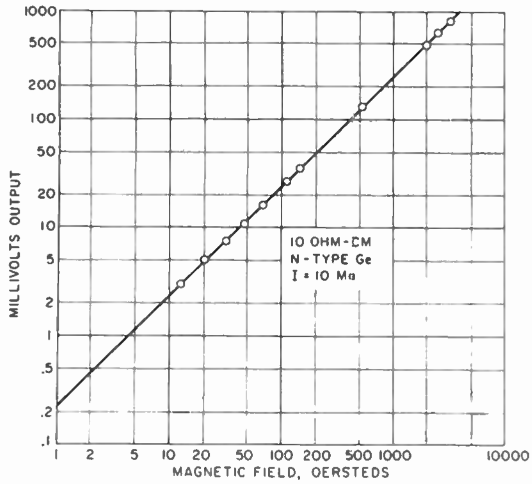

Fig. 7—Output vs field for a germanium Hall element.

low levels. An efficient magnetic design is more important in Hall-effect heads than in ordinary types because the low output voltages which are a fraction of a millivolt do not allow a margin of safety. Leakage and coupling losses should be minimized.

Thickness (T) appears in the denominator of the Hall-voltage equation, and hence should be minimized. Reducing the thickness of the Hall wafer also improves the magnetic efficiency by decreasing the magnetic circuit reluctance. These benefits are accompanied by a smaller cross section in the element with higher ohmic resistance, so that the exciting current (I) must be reduced. Since heating is varied as I^2, the current needs to be reduced only in proportion to the square root of the higher ohmic resistance, and there is a net advantage in thin elements.

Experimental Results

In earlier experiments, we made the Hall elements from germanium. Polycrystalline and single-crystal bulk materials were tried, as well as evaporated films. The single crystal variety turned out to be the most sensitive. A number of heads were built with single crystal germanium, some with elements in the back-gap as in Fig. 3, and others with front elements shaped as in Fig. 6. All of these designs performed satisfactorily. Of the front-gap types, the best results were obtained with the K element of Fig. 6(c).

A characteristic unequalized frequency response curve of a Hall-effect head is shown in Fig. 8. Here the record was made at constant recording current throughout the audio range. Low-frequency output remains constant, and actually goes all the way down to zero frequency. Those who are familiar with constant current curves of ordinary heads (Fig. 1-A) will be disappointed at the apparent "high-end" response of Fig. 8 above 1000 cycles, until we point out that it is really better than Fig. 1-A if we correct for the 6 db per octave rate-of-change rise in Fig. 1-A.

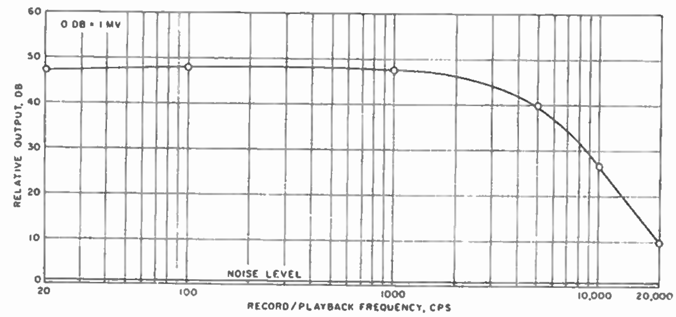

Fig. 8—Unequalized response characteristics of an experimental Hall-effect head.

It is clear that low-frequency equalization may be omitted for a Hall head, but that high-frequency equalization is required to bring its performance to the same level as a conventional head having the same core and gap.

With the germanium elements a noise was generated by passage of the exciting current. Measurements showed that the noise increased in direct proportion to the current, so that when enough excitation was used to bring this noise well above the background noise of the amplifiers, there was no advantage in further increase of excitation since the signal and noise both rose together.

Other semiconductors were also tried in our Hall-effect heads. Indium-antimonide was the best of these by a wide margin, with respect to high sensitivity and low noise. Using this material, we obtained a signal-to-noise ratio of more than 50 db over audio bandwidths. For audio work the variation in sensitivity with temperature change was not noticeable. In instrumentation, where drift is more important, alternative semiconductors may be used at a sacrifice of output for the sake of stability.

Dc excitation of the Hall element is by far the simplest, but when a system must respond all the way down to zero frequency, then we require stable dc amplifiers after the head output, and these are sometimes troublesome. Alternatively, we can energize the Hall element with ac instead of dc, in which case the output will be an ac signal of the excitation frequency whose amplitude depends on the amplitude of the signal picked up by the head, and whose phase depends on the polarity of the signal. Carrier techniques are then applied, including narrow-band amplification, and demodulation to give the analog of the signal. Ac systems were investigated and were found practical. The chief limiations were the additional circuitry required, and the stability against drift from a balanced condition.

Application

Hall-effect heads are the simplest form of detector for pickup of low-frequency information from slowly mov-

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ing tapes. This is advantageous in data analysis, control systems, and instrumentation.

Output of the head is an analog of the recorded magnetic flux. Thus complex waveforms may be reproduced and displayed without phase distortion.

Static sensitivity to very small magnetized areas, in the order of the gap dimensions, makes the Hall head a useful tool for study of the magnetic recording process itself.

High-frequency limitations and nonlinearities of ferromagnetic core and coil construction may be avoided by certain Hall head designs.

Hall-effect heads are also useful for general purposes as for example high-fidelity audio reproduction; but their application in this field depends on economies of production, and relative circuit advantages compared to present day heads.

ACKNOWLEDGMENT

The author is grateful to Dr. J. J. Brophy for his suggestions and for making various semiconductor materials available to this project, to C. Christensen who fabricated the elements and heads, and to P. Padva who tested the heads.

Correspondence

A Network Transfer Theorem*

A simple network theorem, published by Hurtig,[1] seems to have gone unrecognized despite its usefulness. A search of recent texts on network theory does not reveal it, nor does it appear in texts on transistor circuit design, where it would be especially applicable.

The theorem: For a linear, passive, reciprocal two-port network, the forward, open-circuit voltage transfer ratio is equal to the reverse, short-circuit current transfer ratio. The theorem might well be called the Transfer Theorem.

Hurtig suggested the following proof. Consider the network Y in the two connections of Fig. 1. From Thevenin's Theorem,

$$I_s = \frac{E_0}{Z} \quad (1)$$

where E_0 is the output voltage with terminals (b) open circuited, and Z is the impedance at terminals (b) with terminals (a) short circuited. It follows that

$$I = \frac{E}{Z}. \quad (2)$$

But, from the Reciprocity Theorem,

$$I_0 = I_s \quad (3)$$

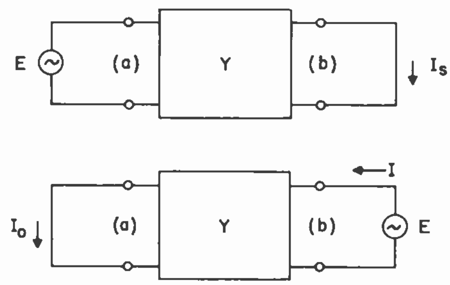

Fig. 1.

so that

$$\frac{I_0}{I} = \frac{I_s}{I} = \frac{E_0}{E} \quad (4)$$

and the theorem is proved.

This result is well known for transformers. Apparently it has not been obvious that it also holds for any linear, passive, reciprocal twoport. It is especially useful in making transitions in design from vacuum-tube to transistor circuits. A vacuum-tube interstage coupling, for example, is usually described by its voltage amplification. The more useful description of a transistor interstage coupling is its current amplification. In many cases, the theorem permits a known vacuum-tube network to be used effectively as a transistor network simply by reversing its ports.

G. FRANKLIN MONTGOMERY
National Bureau of Standards
Washington, D. C.

* Received April 23, 1962.

[1] C. R. Hurtig, "Dual terminations as a guide to practical RC active filter design," *M.I.T. Res. Lab. of Electronics Quarterly Rept.*, pp. 116–117; January 15, 1956.

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Correction to "Average vs RMS Meters for Measuring Noise"*

The author of the above paper,[1] has called the following to the attention of the *Editor*:

There is an error in the figures cited for the deviation of an average reading meter from that of a true rms meter. In the case of a sine wave plus 100 per cent third harmonic, the range of average readings was given as −0.53 db (0° phase) to −6.53 db (180° phase). In fact, this range should be −0.53 db to −1.30 db.

The error resulted from an oversight. Fig. 2(b) shows the waveform under discussion. In calculating the average value, the integration mistakenly was carried out in only two parts: from 0 to π, and from π to 2π. This results in the cross-hatched portions being subtracted from, rather than added to, the main area. To be valid, since full-wave rectification was assumed, the integration must be carried out separately for each of the six parts, with the phase reversals accounted for by proper sign changes. Doing so results in a value for i_{av} of 0.775, rather than 0.425 as was originally given. Line 3 in Table I, therefore, should read:

i_{rms}	i_{av}	rms meter indicates	Average meter indicates	Average meter error (db)
1.000	0.775	1.000	0.861	−1.30

(The same figures also apply to the next-to-last paragraph on page 109.)

The "worst case" condition for third-harmonic distortion actually results when the third harmonic is considerably less than 100 per cent. Because of complications involved with the zero-crossings, detailed calculations have not been carried out, except for the case of 33.3 per cent third harmonic. Under this condition, the average meter error ranges from +0.46 db (0° phase) to −1.48 db (180° phase). Experimental results indicate, however, that this is still not the worst case, but that something approaching 50 per cent third harmonic gives nearly 3-db error.

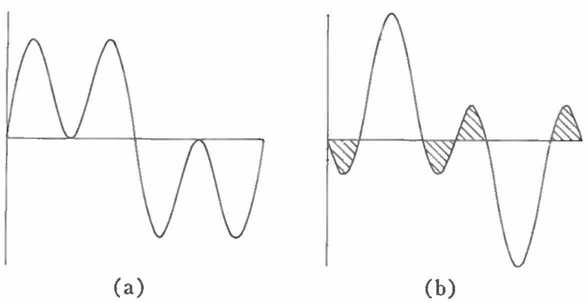

Fig. 2—Sine wave with 100 per cent third harmonic. (a) 0° phase. (b) 180° phase.

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RCA Victor Record Div.
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* Received March 5, 1962.

[1] J. J. Davidson, IRE TRANS. ON AUDIO, vol. AU-9, pp. 108–111; July-August, 1961.

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Contributors

Robert F. Brown, Jr. was born in Lexington, Mass., on January 29, 1927. He received the B.S. degree in engineering physics from the University of Maine, Orono, in 1950.

During World War II he served in the U. S. Navy. From 1950 to the present he has been employed in the Sound Section of the National Bureau of Standards. Starting as a Physicist, he has worked in the fields of sound recording and reproduction, hearing diagnostic instruments, acoustic properties of soils, and instrumentation for infrasonic systems. He was a member of the group chosen in 1959 to receive the Department of Commerce Exceptional Service Gold Medal for its contributions to the science and technology of infrasonic instrumentation and measurement. He is currently an Electronic Engineer engaged in a study of the fundamental processes of magnetic recording, primarily as related to short wavelength recording and reproduction.

Mr. Brown is a member of The Acoustical Society of America, Phi Kappa Phi, Tau Beta Pi, and Sigma Pi Sigma.

❖

Marvin Camras (S'41–A'42–SM'48–F'52), for a photograph and biography, please see page 181 of the September-October, 1961, issue of these TRANSACTIONS.

❖

Frank A. Comerci (SM'55), for a photograph and biography, please see page 100 of the July-August, 1961 issue of these TRANSACTIONS.

❖

Eric D. Daniel (SM'62) was born in London, England, on June 6, 1924. He received the M.A. degree in physics from the University of Oxford, England, where he graduated in 1944.

From 1944 to 1946 he worked on acoustics at the Post Office Research Station, London, England. From 1946 to 1956 he was employed by the British Broadcasting Corporation, London, England, performing basic research in magnetic-tape recording. During his affiliation with the National Bureau of Standards, Washington, D. C., from 1956 to 1959, his principal project was the establishment of tests and specifications for magnetic tape. From 1959 to 1961 he was employed by Ampex Corporation, first as Senior Staff Physicist at Redwood City, Calif., and, later, as Head of Research of the Ampex subsidiary in Reading, England. He is presently Associate Technical Director of Memorex Corporation, Santa Clara, Calif.

❖

Donald F. Eldridge (A'50–M'55–SM'60), for a photograph and biography, please see page 181 of the September-October, 1961, issue of these TRANSACTIONS.

❖

Florence Nesh was born in Brooklyn, N. Y. She received the B.S. Degree in chemistry from Long Island University, Brooklyn, N. Y., and the M.S. degree in physical chemistry from New York University, N. Y.

Subsequently, she affiliated with the Sloan-Kettering Institute for Cancer Research, New York, N. Y., where she developed a radioisotope correction technique for the determination of blood iodine. While in the Physical Chemistry Section of the Material Laboratory, New York Naval Shipyard, she published papers and received patents in the fields of analytical method development, product development, ion-exchange, electron-microscopy, chemical kinetics, radiochemistry, and ultrasonics. At present she is with the Magnetic Recording Group of the Sound Section, National Bureau of Standards, Washington, D. C.

Miss Nesh is a member of The Scientific Research Society of America, The American Chemical Society, and The Acoustical Society of America.

❖

Charles J. Peters (S'50–M'58) was born in Vandergrift, Pa., on March 14, 1929. He received the B.S., M.S. and Ph.D. degrees in electrical engineering from Carnegie Institute of Technology, Pittsburgh, Pa., in 1951, 1952 and 1954, respectively.

From 1953 to 1955 he was with the Gulf Research and Development Company, in Pittsburgh, Pa., where he was concerned with multiphase fluid flow through porous media as it pertains to oil reservoir performance. In 1955 he was called to active duty in the U. S. Army and was stationed at White Sands Proving Grounds where he worked on missile countermeasures. During his military service he was also an Assistant Professor of Electrical Engineering at the New Mexico College of Agriculture and Mechanic Arts, State College. In 1957 he joined the Applied Research Laboratory of Sylvania Electronic Systems, a Division of General Telephone and Electronics, Waltham, Mass., where he continued his work on countermeasures and became engaged in projects on magnetic-tape recording and laser communications devices.

Dr. Peters is a member of Eta Kappa Nu and Tau Beta Pi.

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The IRE Professional Group on Audio is grateful for the assistance given by the firms listed below, and invites application for Institutional Listing from other firms interested in Audio Technology.

BALLANTINE LABORATORIES, INC., Boonton, N.J.
AC Voltage Measuring Instruments (0.01 cps-1000 Mc), Laboratory Voltage Standards (0-1000 Mc)

JAMES B. LANSING SOUND, INC., 3249 Casitas Ave., Los Angeles 39, Calif.
Loudspeakers and Transducers of All Types

JENSEN MANUFACTURING CO., Div. of The Muter Co., 6601 S. Laramie Ave., Chicago 38, Ill.
Loudspeakers, Reproducer Systems, Enclosures

KNOWLES ELECTRONICS, INC., 10545 Anderson Place, Franklin Park, Ill.
Miniature Magnetic Microphones and Receivers

SHURE BROTHERS, INC., Evanston, Ill.
Microphones, Phonograph Pickups, Magnetic Recording Heads, Acoustic Devices

UNITED TRANSFORMER CORP., 150 Varick St., New York, N.Y.; 3630 Eastham Dr., Culver City, Calif.
Transformers, Inductors, Electric Wave Filters, High Q Coils, Magnetic Amplifiers, Pulse Units

Charge for listing in six consecutive issues of the TRANSACTIONS—$75.00. Application for listing may be made to the Professional Groups Secretary, The Institute of Radio Engineers, Inc., 1 East 79 Street, New York 21, N.Y.

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