# IRE Transactions on AUDIO

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### CONTRIBUTIONS

### CORRESPONDENCE

PUBLISHED BY THE

**Professional Group on Audio**

## 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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## IRE TRANSACTIONS® ON AUDIO

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World Radio History

# The Editor's Corner

*Apropos to The Editor's Corner for May–June, 1961, B. F. Miessner, Fellow of the IRE, and famous for his many inventions, has sent us the following.**

Titillated by your Editor's Corner "Report," in the current issue of these TRANSACTIONS, I cannot resist the observation that it is really more fact than a tale of fiction, dreamed up by a secret society of intellectual funsters.

If anyone thinks otherwise about the vision, the sagacity, and the pioneering spirit of our modern "Captains of Industry," let him read Henry Mencken's collection of essays in his "Chrestomathy." "Intellectual lethargy," "incurable ingenuousness," "appalling lack of common sense," "preposterous caricatures of God," "blank cartridges," are a few of his characterizations. Quoting briefly: "Charles Francis Adams, a grandson of one American President, and a great grandson of another, after a long lifetime in intimate association with some of the chief business 'genuises' of the United States, reported in his old age that he had never heard a single one of them say anything worth hearing."

That Bell's proposals met with skepticism, even derision, and innumerable objections, is hardly surprising. Besides, admitting all of these to be utter nonsense, would not such a system of *voice* communication threaten the very foundations of an already entrenched telegraph system?

Have we not, those of us old enough to remember, seen the same sort of situation in the acceptance of *radio* communication?

How about electric illumination? Can you not hear the stinging objections of the gas lighting industry when Edison proclaimed the perfection of his electric lamp? "What! You expect us to discard all of our coke ovens, our gas wells, our system of distribution pipes, our huge pressure regulating storage tanks, as well as the millions of meters, gas lighting fixtures, burners and the like? Then to replace these with electric power houses, distribution lines, house wiring, electric meters, and other millions of electric lighting fixtures and lamps?"

"You ask *us* to throw all of that overboard for your new gadget and your visions of a world lighted by a mysterious something you call electricity, which can kill by mere and momentary contact?"

And so it goes. Henry Ford tried desperately to get backing in Buffalo for his "tin lizzie" and failed. Every wagon maker but one (Studebaker) laughed him out of their mahogany-studded directors' rooms. Yet, from their wagons to his Model T was only a little hop, skip and jump. And, with all of the modern ballyhoo about automotive perfection, all still use the modern version of the carriage lamp, which cannot see around corners where the cars are going!

Look where you will in any industry and you will find the same lack of vision, the same mental inertia, the same preference for complacent peace over the brain sweat in learning (like old dogs) the new tricks of Progress. The deeper is their entrenchment, the more resistant is their determination to stick with what they have. Like the Colorado River in the Grand Canyon, their vision, if any they have, to far horizons is blocked by the results of their own past energies, and they cannot escape.

Historians of technology have clearly shown that the incubation period for radically new methods of doing old things, or for entirely new things, averages about 40 to 50 years! The one notable contrary example which proves that rule is atomic and nuclear energy development, and that was a very major and national undertaking during a dire international emergency.

That I speak (at 71, *today*) from bitter experience over the mental obesity of our nation's governmental and industrial leadership can be illustrated by a, I hope pardonable, personal reference to guided and target-seeking missilry, which we now have only after 50 years of do-nothingness by the powers that be in our beloved country.

In the fall of 1912, Jack Hammond and I demonstrated unerring and precise radio guidance of a high-speed motor boat (representing a surface-riding torpedo) in Gloucester Harbor and beyond, as far as the aided eye could see, before the top brass of our Coastal Defense Department. By 1916, nothing having been done in fuller development for naval hardware, I published a book, "Radio Dynamics" (D. Van Nostrand Co., Inc., New York), while a 26-year-old student at Purdue University. It disclosed not only the principles of modern multiplex radio communication with the IF introduced into the transmitted RF carrier, and with an additional AF modulation, plus the now-familiar double detection (also *triple* detection, for dc relay operation) of our superheterodyne receiver system, but it also disclosed the principles of infrared, target-seeking missiles, all conceived by myself and at least preliminarily tested in 1911–1912.

The very least that this experience has proven is that what is not understood is rarely if ever believed by those who must make the decisions for development and use of radically new ideas.

So the "Report of Special Technical Committee to Determine Market Opportunities for the Telephone" cannot be far from the truth, whether fact *or* fancy.

BENJAMIN (FRANKLIN) MIESSNER
680 North East 105th St.
Miami Shores, Florida

*(The Editor's Corner welcomes your views. Please send them in.*—MARVIN CAMRAS, *Editor)*

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* Received by the PGA, August 21, 1961.

# PGA News

## MINUTES OF THE MEETING OF THE ADMINISTRATIVE COMMITTEE

**New York, N. Y., March 20, 1961**

*Members Present*

H. S. Knowles, *Chairman*
P. C. Goldmark, *Vice Chairman*
R. W. Benson
A. G. Bereskin
M. Camras
M. Corrington
J. R. Macdonald
B. B. Bauer, *Secretary-Treasurer*

*Newly Elected Members Present*

D. Brinkerhoff
F. A. Comerci
H. E. Roys, *Vice Chairman*, 1961–1962
B. Wayne[1]

*Members Absent*

C. M. Harris, *Chairman*, 1961–1962
J. K. Hilliard

*Guests Present*

R. A. Heising, *IRE Representative*
M. Copel
D. W. Martin
S. W. Schram
W. M. Ihde

The meeting was held at the Waldorf-Astoria and was called to order at 8:30 P.M.

### 1) *Approval of Minutes of the Last Two Meetings*

Upon motion of M. Corrington, seconded by J. R. Macdonald, the minutes of the Administrative Committee dated March, 1960, and October, 1960, were approved by unanimous vote.

### 2) *Results of Election*

The final results of the PGA election as advised by IRE Headquarters, were reported by the Chairman as follows:

C. M. Harris—*Chairman*, 1961–1962
H. E. Roys—*Vice Chairman*, 1961–1962

The newly elected Administrative Committee members are as follows:

D. Brinkerhoff—1961–1964
F. A. Comerci—1961–1964
B. Wayne[1]—1961–1964

The Secretary stated that the current operation of the Group appeared to be based upon the 1949 Constitution and Bylaws as amended on January 5, 1955. In accordance with this Constitution and Bylaws, there are 9 members of the Administrative Committee, including the Chairman of the Group, 3 new members being elected each year for a period of three years. If the Chairman and Vice Chairman elect are not holdover members of the Administrative Committee, then a correspondingly smaller number of new members are declared elected.

In accordance with the new Constitution and Bylaws, which are in the process of being amended, there will be a Chairman and 9 members of the Administrative Committee. The Chairman is elected for one year and, if he is serving an unexpired term at the time he takes office, his membership in the Administrative Committee terminates at the time of his election to Chairmanship. The new Constitutional amendment, published in the January–February, 1961, issue of these TRANSACTIONS, will be effective within 30 days of publication, unless 10 per cent of the members object.

In the event that it is determined that the present election was conducted in accordance with the 1955 Constitution and Bylaws, since Roys is not a holdover member of the Administrative Committee, only Brinkerhoff and Comerci will be declared elected as new members of the Administrative Committee, and the newly elected Chairman Harris will remain a member of the Committee until 1963.

In the event that the new Constitution and Bylaws apply, then Harris will have been elected Chairman for the year 1961–1962 and, unless re-elected thereafter, he will no longer be a member of the Administrative Committee. In addition, B. Wayne will have been elected a member for the period 1961–1964.

The Secretary will attempt to clarify the applicability of the old or new Constitution and Bylaws, in cooperation with Chairman Harris and the IRE Headquarters.

A motion was made by M. Camras, seconded by R. W. Benson, and passed unanimously, to approve this report.

### 3) *Report of the Editorial Committee*

Editor Camras stated that everything seems to be under control, and he is satisfied with the way things are going. One important problem is that the authors sometimes make a commitment of their papers to other publications, prior to presentation at the IRE meetings and at the NEC. Chairman Knowles asked R. A. Heising what the policy on this matter was as far as

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[1] The status of B. Wayne will be determined from the pending interpretation of the Constitutional amendment published in the January–February, 1961, issue of these TRANSACTIONS.

IRE Headquarters was concerned. Heising replied that a statement of policy could be obtained from E. K. Gannett, Managing Editor.

Camras also stated that an especially meritorious paper could be published by the IRE-PGA even though it had been published elsewhere, and that the Audio Engineering Society followed the policy that papers presented before the AES could not be published elsewhere.

B. B. Bauer suggested that the IRE require the prospective authors to agree to give the IRE the option to publish their papers in one of the IRE publications, prior to publication elsewhere.

Chairman Knowles suggested that the Chairman-Elect take this matter up at the next Professional Groups Committee meeting.

Various suggestions were made for improved ways for procuring, editing and reviewing papers, which Editor Camras took under advisement.

### 4) *Discussion of the Scope of PGA*

At the suggestion of P. C. Goldmark, Chairman Knowles opened the subject of a letter of March 13 from D. F. Eldridge, who is sponsoring the formation of a professional group on recording. Eldridge's letter states in brief that he would like to ask the IRE again for a charter for a group on recording, but in the event this is unsuccessful, that he would then seek an affiliation with the Professional Group on Instrumentation. Therefore, Eldridge requests that the PGA make a resolution that would have a favorable effect upon the Professional Groups Committee in granting this charter.

Chairman Knowles stated that he pointed out to Eldridge that recording is within the field of interest of the PGA, and that the scope of this interest was clarified by the Administrative Committee of PGA last fall by omitting the limitation "at audio frequencies" from the statement of the field of interest; furthermore, this amendment has been approved by the Professional Groups Committee and the Executive Committee of the IRE.

It was the general consensus that the PGA would continue to provide a forum for all meritorious papers on recording, including magnetic recording as in the past. Moreover, the PGA would continue to offer opportunities for those with recording interests to become active in Editorial and other Committee work.

A. G. Bereskin moved that the PGA restate its scope and interest in the field of recording and convey this information to the promoters of a professional group on recording. This was seconded by Camras and adopted unanimously.

Thereupon, Chairman Knowles offered the suggestion that the new PGA Chairman take the following action:

> The Chairman of the PGA replying to Mr. Eldridge's letter will state that the scope of the PGA now stands as follows:
>
> *Article III—Field of Interest*
>
> Section 1. The Field of Interest of the Group shall be the technology of communication at audio frequencies and of the audio-frequency portion of radio frequency systems, including the acoustic terminations and room acoustics of such systems, and the recording and reproduction from recordings, and shall include scientific, technical, industrial or other activities that contribute to this field, or utilize the techniques or products of this field, subject, as the art develops, to additions, subtractions, or other modifications directed or approved by the IRE Committee on Professional Groups.
>
> The Administrative Committee at the meeting of March 20, 1961, has expressed the consensus that there is no reason to alter the above scope and offers the suggestion that Mr. Eldridge's group formulate its field of interest, so as not to conflict with the PGA.
>
> The Professional Group on Audio desires to continue to cooperate in every way in serving as a forum for presentation and publication of papers on magnetic recording as well as other forms of recording.

Upon motion by Camras, seconded by Benson, this suggestion was adopted unanimously.

### 5) *Report of Fall Meeting Study Group*

The following report was made by S. W. Schram (WADD representative for Tober Mountz, who could not be present at the meeting) in connection with a meeting on Military and Space Communication Acoustics, proposed by Harris.

Schram stated that WADD does not have a relatively large program in Audio, and that he could not find anyone who would have enough enthusiasm to organize a meeting on Audio there.

He suggested that the Midwest interests could be served by joining with the Spring Conference in Cincinnati. It was felt by the Dayton Chapter that the Cincinnati people could run it more successfully. Also, the Professional Group on Military Electronics Conference in Washington, the Ultra Communications Conference in Rome, or the N.A.C. in May, perhaps might be more suitable.

Schram advised that he was very sorry, but a negative reply would have to be given by Dayton.

D. W. Martin felt that if the Dayton people were willing to take on a major part of the local responsibility, then the Cincinnati Chapter would cooperate. However, Cincinnati will be host to a number of meetings this fall, among them the Acoustical Society in November. Martin suggested that possibly the Acoustical Society may wish to have a session of their Conference in the field of Military Acoustics, cosponsored by the PGA.

At the conclusion, it was suggested by Chairman Knowles that these ideas be conveyed to the forthcoming Administrative Committee for action.

### 6) *Program Committee*

M. Copel gave a brief report on the Convention papers. Chairman Knowles then reviewed the plans for the PGA Meeting to be held the next day during the Audio Session. Normally, during this meeting the outgoing Chairman announces the results of the election and introduces the new members of the Administrative Committee and the winners of the PGA Awards, and the Secretary-Treasurer gives a brief financial report. Thereupon, the outgoing Chairman presents a symbolic gavel to the new Chairman, who makes a few brief remarks about the plans for the new year. In view of the illness of Chairman Harris, the last part of the meeting will not be performed this year. Chairman Knowles then announced that the PGA meeting would be held about 11:30 A.M. during the Audio Session of March 21, and Copel agreed to make the necessary arrangements with the Session Chairman.

### 7) *Finance Committee*

The Report of the Finance Committee (below) was presented by the Secretary-Treasurer Bauer. This report, dated February 14, was sent to the Administrative Committee outlining the financial status of PGA. The publication expense is currently $3.00 per year per member; the former IRE contribution has been reduced to one-third of the publication expense, which has been alloted to PGA at a $6000 per year rate, while the actual expense is at a rate of some $12,000 per year. PGA is believed to have lost some membership as a result of the common billing, which now places each Group in competition against another 27 Groups for the member's dollar. Unless the assessment is raised to $3.00 the PGA balance will continue to decrease and will become exhausted in about four years.

The ensuing discussion pointed out that the IRE seemed to favor the action of preventing large balances from being credited to the Groups, and that therefore it appeared desirable to allow the PGA balance to diminish to an appropriate level.

By motion of Bereskin, seconded by Comerci, it was resolved unanimously to continue the present PGA financial policy until the balance in the treasury reaches an appropriate level. The Secretary-Treasurer is charged with the responsibility of corresponding with IRE Headquarters and ascertaining what is considered to be an appropriate balance level for a group of the general size of PGA.

By motion of Corrington, seconded by Macdonald and carried unanimously, it was resolved to set the assessment for the year 1961–1962 at $2.00 per year.

### 8) *Awards Committee*

The Awards Committee headed by Bereskin presented its nominees as outlined below.

Furthermore, the Committee recommended that the name of William B. Snow be submitted by the PGA for the IRE Fellow Award, the deadline for submitted nominations being March 31.

By motion of Bereskin, seconded by Comerci, the report and nominations were approved unanimously, and the Secretary was directed to implement them in the customary manner.

### 9) *Ways and Means Committee*

Copel presented the Report of the Ways and Means Committee (below). The Committee reports that $450 has been received for the year in Institutional Listings, and recommends that the Committee be authorized to handle solicitations, renewals and follow-ups directly.

By motion of Corrington, seconded by Macdonald, this report was approved unanimously.

### 10) *Acceptance of Reports*

By motion of Corrington, seconded by Macdonald, all the reports were accepted.

### 11) *Proposal for Further Constitutional Amendment*

With revision of the Constitution and Bylaws having been successfully consumated by the Committee headed by Corrington, Corrington indicated that he preferred that a new Chairman be appointed to head this committee. Knowles accepted this suggestion with thanks on behalf of the Administrative Committee and the PGA for the long and arduous task which has given PGA a superior Constitution and Bylaws.

Chairman Knowles offered the following proposition raised by Chairman-Elect Harris: When a Chairman is elected without having been a member of the Administrative Committee he comes into the office "cold" and cannot operate effectively. It might be desirable to propose a change in the Constitution that would serve to remedy this deficiency. A discussion was directed to a possibility of providing for a Chairman-Elect who would be a member of the Administrative Committee for a period of one year before taking over as Chairman. Chairman Knowles referred this suggestion to the Committee on Constitution and Bylaws for further consideration.

### 12) *Appointment of Committee Chairmen*

Knowles read the following appointments for Committee Chairmanships:

*Editorial*—Marvin Camras
*Papers*—Frank Comerci
*Chapters*—William M. Ihde
*Awards*—J. Ross Macdonald
*Nominations*—Daniel Martin
*Constitution*—H. E. Roys
*Secretary-Treasurer*—Benjamin B. Bauer

### 13) *Forthcoming Meeting*

After brief discussion, Chairman Knowles selected the afternoon of Saturday, November 11, for the next meeting of the Administrative Committee, to coincide with the Acoustical Society Meeting in Cincinnati this fall. Chairman-Elect Harris will be requested to confirm this date and apprise the Committee members of the exact time and place.

BENJAMIN B. BAUER
*Secretary-Treasurer*

## REPORT OF THE CHAPTERS COMMITTEE

Since his appointment in November to fill out J. R. Macdonald's term, the undersigned has contacted all of the PGA Chapters asking for statements of their activities. San Antonio, Milwaukee, and Philadelphia have responded.

IRE Headquarters has also been solicited for copies of a tabulation of PGA members by Section. A letter to the Chairmen and the Professional Group Coordinator of the Sections having over 30 members, and which showed an increase over the previous year, has been sent together with a list of the local PGA members requesting assistance in the formation of a local Chapter.

All information which has been received so far about Chapter activity has been forwarded to the Editor of these TRANSACTIONS for publication.

WILLIAM M. IHDE

## REPORT OF THE FINANCE COMMITTEE

February 14, 1961

This is a report on the financial status of PGA, as of Spring, 1961. It is also intended as basis for discussion of the future of PGA.

1) Please refer to the following columns of figures.

| Status on December 31 | Year's Publication Expense | Number of Members | Number of Students |
|---|---|---|---|
| 1956 | $ 7893 | 3259 | 550 |
| 1957 | 7328 | 3892 | 608 |
| 1958 | 8562 | 3736 | 612 |
| 1959 | 11,034 | 4846 | 557 |
| 1960 | 12,749 | 4106 | 445 |

You will notice that our publication expense has been growing at a rapid rate. Because of a change in accounting procedures, the year-end statement during the last two years has shown the publication expense for the first 5 issues during the year, plus the last issue of the preceding year. This has thrown some confusion in our projected publication cost. However, the trend is clear.

I would like to suggest that a study be made in cooperation with Editor Camras of the number of pages we publish, the cost per page, and other figures which will indicate what we are likely to do in the future, with respect to publication expense.

2) The number of members has been growing steadily until 1959, but in 1960 there was a considerable drop. I believe this was caused by the change of billing procedure on part of the IRE. At one time, each group billing went out separately; now the member receives a card on which he checks off the group in which he is interested. It is evident that being confronted with a single large bill the members have been more selective than before. In a sense, we are competing against the interests and the appeal of 27 other Professional Groups.

What to do to insure future healthy growth of PGA in the light of these conditions?

3) From 1958 onward, the number of student members has been decreasing. Some time ago the PGA established a students award and engaged in various activities which promoted student membership, such as cooperation with the IRE STUDENT QUARTERLY. Lately, these activities appear to have ceased. Perhaps a committee should be appointed to look into student activities, and to work with the Student Chapters.

4) I am enclosing a revised budget estimate for 1961. You will notice that we are starting the year with $15,000; assuming an income corresponding to current membership, with an IRE subsidy of $3,000 and expenses equal to last year's, we will end the year with $13,200.

5) The PGA assessment has been $2.00 since the start of the Group. At present, 12 Groups charge $2.00, 12 charge $3.00, and 4 charge $4.00.

6) Lest there be concern, let me reiterate that our balance in the Treasury is still about equal to one year's expenses, which is better than most Groups' performance. IRE has cut down our publication subsidy to trim our balance, since there appears to be a desire to help improvident Groups at the expense of those that have been well managed. Nevertheless, in my opinion we should run the organization with a balanced budget, and in the long run the Group should seek means for either trimming $2500 of the annual expense or raising its annual income by a similar amount. The desirability of raising the assessment to $3.00 in the future should be considered.

## ESTIMATED BUDGET

### January 1, 1961–December 31, 1961

| | | | |
|---|---|---|---|
| 1) | Balance from December 31, 1961 | | $15,600 |
| *Receipts During Period* | | | |
| 2) | Membership Fees | $ 8200 | |
| 3) | Sale of Publications | 600 | |
| 4) | Advertising | 300 | |
| 5) | Surplus from Meetings | — | |
| 6) | IRE Subsidy (⅓ of item 10) | 3000 | |
| 7) | Others | — | |
| | | $12,100 | |
| 8) | Total Receipts | | $12,100 |
| 9) | Total Balance and Receipts | | $27,700 |
| *Expenses During Period* | | | |
| 10) | Publication | $12,800 | |
| 11) | Membership Service Charges | 300 | |
| 12) | Group Awards | 500 | |
| 13) | Editorial Administrative Expenses | 100 | |
| 14) | Other | 800 | |
| 15) | Total Expenses | | $14,500 |
| 16) | Balance as of December 31, 1961 | | $13,200 |

BENJAMIN B. BAUER
*Secretary-Treasurer*

## PGA AWARDS COMMITTEE REPORT

This Committee submits the following nominations for the specified awards:

*IRE-PGA Achievement Award*

William B. Snow—for "outstanding contributions to Audio Technology."

*IRE-PGA Senior Award*

Donald F. Eldridge—for his paper "Magnetic Recording and Reproduction of Pulses," in the March–April, 1960, issue of the IRE Transactions on Audio.

*IRE-PGA Award*

William D. Roehr—for his two papers "A Two Watt Transistor Audio Amplifier," and "Characteristics of Degenerative Amplifiers Having a Base Emitter Shunt Impedance," in the September–October, 1959, and November–December, 1959, issues, respectively, of IRE Transactions on Audio.

Previous recipients of the IRE-PGA Achievement Award and the years in which the awards were made are listed below:

1955—B. B. Bauer
1956—H. F. Olson
1957—H. E. Roys
1958—M. Camras
1959—D. W. Martin
1960—A. B. Bereskin
P. C. Goldmark

A. B. Bereskin
*Chairman*

## REPORT OF WAYS AND MEANS COMMITTEE

This report covers the period from March 1, 1960, to February 28, 1961.

1) Four Institutional Listings which expired during this period were renewed and paid.

2) In view of the drop in income from Institutional Listings in these Transactions, this Committee discussed the situation with Chairman Knowles in October, during the Acoustical Society Meeting in San Francisco. It was agreed that the direct solicitation and follow-up by this Committee should be resumed, since personal contacts were usually more effective in securing subscriptions. Chairman Knowles agreed to write to L. G. Cumming in an effort to clarify this situation. However, the correspondence did not yield any satisfactory results. In January, 1961, this Committee started direct personal solicitation through professional contacts. In all, twelve companies were approached. Two subscriptions were received, Telephonics Corporation and Ballantine Laboratories, Inc. Two companies answered negatively, but indicated the possibility of subscribing next year.

3) It is the recommendation of this Committee that, if it is desired to increase the PGA's income from Institutional Listings, the Ways and Means Committee be authorized to handle solicitations, renewals, and follow-ups directly, and that headquarters be advised of same.

4) Total receipts for the year were $450.

5) The records of the committee are in good order.

Michel Copel
*Chairman*

## CHAPTER NEWS

Chicago, Ill.—Our Chicago Chairman, Jim Novak, reports that the Fall Season will be a full one starting in September.

Three joint meetings are scheduled with other Professional Groups or Professional Societies. The Chicago PGA Chapter has found this manner of meeting very successful, since a larger audience is afforded to the speaker and two or three meetings can be held simultaneously. Perhaps more Chapters could make use of this method of scheduling meetings.

The Chicago PGA schedule is as follows:

September 20, 1961
Joint with Professional Group on Instrumentation.
Title: "High-Speed Testing of Audio Amplifier in Production"
Speaker: Earl Bockenfeld, Hammond Organ Company
Place: Black Steer Restaurant
6446 West North Avenue
Chicago, Ill.

October 13, 1961
Joint with Chicago Acoustical and Audio Group.
Title: "Stereo Geometry"
Speaker: Paul Klipsch, Klipsch Associates
Place: Western Society of Engineers

November 14, 1961
Joint with Professional Group on Military Electronics.
Title: "Under Water Image Projection" (Ultra Sonics)
Speaker: Henry Karplus, Armour Research Foundation
Place: Illinois Institute of Technology

William M. Ihde

# A New Model for Magnetic Recording*

B. B. BAUER†, FELLOW, IRE, AND C. D. MEE†, SENIOR MEMBER, IRE

*Summary*—Magnetic recording is a complicated process which has in the past been portrayed largely in terms of models based upon the magnetic characteristics of the recording medium. The previous models have been incomplete and sometimes incorrect, and they have left unexplained many of the experimental phenomena known to exist in magnetic recording. The proposed new model is not claimed to be precise in every detail. However, it has the virtue of presenting a unified and simplified picture of magnetic recording. The recording process is viewed as an interaction between the idealized properties of magnetic particles and the idealized geometry of the recording field. The latter appears as a series of "bubbles" and "shells" of critical field strengths which grow and collapse throughout the cycles of bias and record current.

## INTRODUCTION

THE magnetic recording process is extremely complicated and difficult to analyze. This is particularly true of the most common technique, which involves the use of a high-frequency bias and short signal wavelengths. It is necessary to know such properties of the recorded tape as remanent intensity of magnetization as a function of applied field strength, direction, and frequency in order to assess the final magnetization of an element of tape after it has passed through the recording zone of the head. Likewise, the recording field pattern seen by any element of the tape must be calculated. This will include a knowledge of the relation between the applied field vector and the position of the element considered with respect to the field source. No theoretical treatment has yet been evolved to take all these effects into account. The most detailed treatments published recently[1–4] look upon the recording process for a tape element as a modified anhysteretic magnetization process. Some difficulty is being encountered in explaining the anhysteretic magnetization properties of magnetic tape materials due to inadequate knowledge of the magnetic interaction between the particles in tape. Models have been used as a start in this problem, and one which assumes a fixed distribution of interacting fields (the Preisach diagram) has been used[2–4] with success. In addition, some quantitative work[5,6] on estimation of interaction fields has also been reported. When these recording functions have been completely analyzed, it will then be possible to study how the magnetizations acquired by each tape element cooperate to produce the reproducing head flux.

As is common in other branches of science, models of magnetic recording have been used to enable workers in the field to visualize better the processes involved. A new model is presented here which aims at depicting the magnetization pattern acquired by the recording medium for various recording techniques in current use. Account is taken of the space-time relationship of the recording field in the vicinity of the record head where the magnetic material is irreversibly affected by the field. Drastic simplifications have been made with regard to the detailed shape of the recording field, the mechanism of magnetization of the tape material, and the interactions with the reproducing head, in order to give clarity to the dynamic geometry of the recording process. It is realized that the physical interpretation of the recording mechanism is not advanced by such a model. Rather, the aim is to provide a unified picture of the process that is sufficiently simple to help a newcomer to understand what is going on and sufficiently accurate to explain the experimental results that are being obtained.

## MAGNETIC RECORDING MODEL

The model to be discussed is primarily concerned with the space-time character of the recording field with respect to the moving tape. For clarity, considerable simplifications are made in the characteristics assumed for magnetic properties of the coating and the recording field contour. This is done with the realization that inclusion of practical conditions will sometimes modify the results obtained. However, the simplifications made are such that a variety of magnetic recording phenomena may be explained in a graphic fashion.

### *Magnetic Tape Model*

It is assumed that the tape coating consists of a uniform distribution of identical magnetic particles, each being magnetically isolated from its neighbors. Moreover, it is assumed that the tape responds only to the longitudinal component of the applied field and that its

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* Received by the PGA, March 27, 1961. Reprinted from the 1961 IRE INTERNATIONAL CONVENTION RECORD, pt. 2, pp. 61–68.

† CBS Laboratories, Div. of the Columbia Broadcasting System, Stamford, Conn.

[1] W. K. Westijize, "Studies on magnetic recording," *Philips Res. Repts.*, vol. 8, pp. 245–269; January, 1953.

[2] E. D. Daniel and I. Levine, "Experimental and theoretical investigation of iron oxide recording tape," *J. Acoust. Soc. Am.*, vol. 32, pp. 258–267; January, 1960.

—— and ——, "Determination of the recording performance of a tape from its magnetic properties," *J. Acoust. Soc. Am.*, vol. 32, pp. 258–267; February, 1960.

[3] J. G. Woodward and E. Della Torre, "Particle interaction in magnetic recording tapes," *J. App. Phys.*, vol. 31, pp. 56–62, January, 1960; vol. 32, pp. 126–127, January, 1961.

[4] G. Schwantke, *Frequenz*, vol. 12, pp. 383–394; December, 1958.

[5] D. F. Eldridge, "Quantitative determination of the interaction fields in aggregates of single domain particles," *J. Appl. Phys.*, vol. 32, pp. 247S–249S; March, 1961.

[6] L. Neél, "Remarques sur la theorie des proprietes magnetiques des substances dures," *Appl. Sci. Res.*, vol. B-4, pp. 13–24; 1954.

magnetization loop is the same as those of the individual particles, *i.e.*, rectangular. These conditions are fulfilled in part by present day tapes consisting of needle-shaped single domain particles oriented in the longitudinal direction of the tape. Ideally, such particles have rectangular hysteresis loops when magnetized along their major axis. Practical tape coatings will depart from ideal, since variations in particle size and shape as well as clumping result in a spread of critical fields for switching the magnetization of the particles. In addition, the probability exists that the fields of neighboring particles cause sufficient particle interaction to modify the local fields acting when an external signal field is applied. The effects of interactions and particle variations are significant in tape recording, and current effort[1–4] is being directed towards their quantitative analysis.

### *Recording Field Model*

The recording field considered here is the component of the external field existing parallel to the direction of tape motion over an infinitesimal gap between pole pieces of infinite permeability. Fig. 1 shows the tape motion and gap direction referred to $x$ and $y$ coordinates existing parallel to the tape motion and perpendicular to the head-tape contact plane respectively. The field ($H$) produced at a distance ($R$) from the gap by a current ($i$) in the winding-around head core is given by

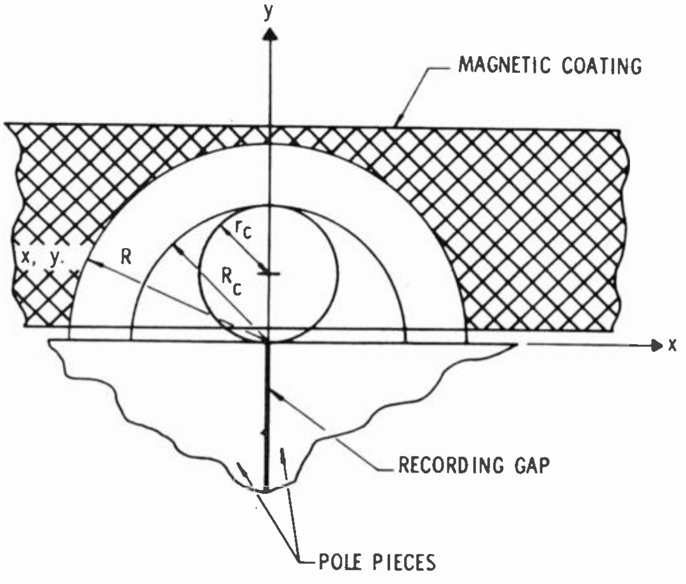

Fig. 1—Magnetic recording model.

$$H = \frac{4ni}{R} \cdot \tag{1}$$

The component of this field parallel to the tape motion ($x$ axis) is

$$H_x = \frac{4niy}{x^2 + y^2} \cdot \tag{2}$$

Assuming a single value critical field ($H_c$) for magnetization of the particles, the locus of the boundary for which $H_x = H_c$ is given by

$$x^2 + y^2 = \frac{4ni}{H_c} \cdot y \tag{3}$$

or

$$x^2 + (y - r_c)^2 = r_c^2 \quad \text{where} \quad r_c = \frac{2ni}{H_c} \cdot$$

This is a circle of radius $r_c$ with center at the point $(0, r_c)$ (see Fig. 1). The applied field inside the circle, being greater than $H_c$, is sufficiently large to magnetize the magnetic material completely, whereas outside the circle it is less than $H_c$ and the magnetic material remains unmagnetized. The diameter of the magnetization "bubble" $R_c$ $(x = 0)$ is given by

$$2r_c = R_c(x = 0) = \frac{4ni}{H_c} = \frac{4n}{H_c}(i_B + i_S) \tag{4}$$

where $i_B$ and $i_S$ are bias and signal currents, respectively.

Eq. (4) indicates that the diameter of the magnetization circle is proportional to the sum of the signal and bias currents. Thus, the magnetization circle can be visualized as a recording bubble whose size varies in accordance with the applied signal for constant bias. The degree to which the model of a circular magnetization bubble in oriented acicular particle tape applies in practice has been shown in a recent paper on visible tape patterns.[7] External demagnetizing fields set up by the magnetic medium combine with the magnetizing field to prevent the formation of a sharply defined bubble.

The model of the recording process thus consists of a cylindrical volume of longitudinal magnetization, tangent to the recording head gap, penetrating the moving tape with an instantaneous diameter proportional to the total instantaneous recording current. It is assumed that a two dimensional representation, replacing the cylinder by a circle, is valid. The model is primarily applicable to long wavelength recording phenomena where the magnetization acquired by the surface layers is not overriding. For tape layers at a distance from the head small compared to the gap length the effect of the perpendicular field cannot be ignored.

Eq. (4) indicates that, for the model, the recorded magnetization is proportional to the recording head current. On the other hand, the remanent magnetization characteristic of the magnetic material is highly nonlinear. The degree to which a narrow-gap recording head (0.2 mil) linearizes the effective magnetization characteristic is shown in Fig. 2. It is seen that a relatively smaller field is required to commence magnetization compared to that required for saturation in the case of a recording head field.

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[7] W. P. Guckenburg and C. D. Mee, "Visible magnetic recordings," *Audio Engrg.*, vol. 9, pp. 107–110; April, 1961.

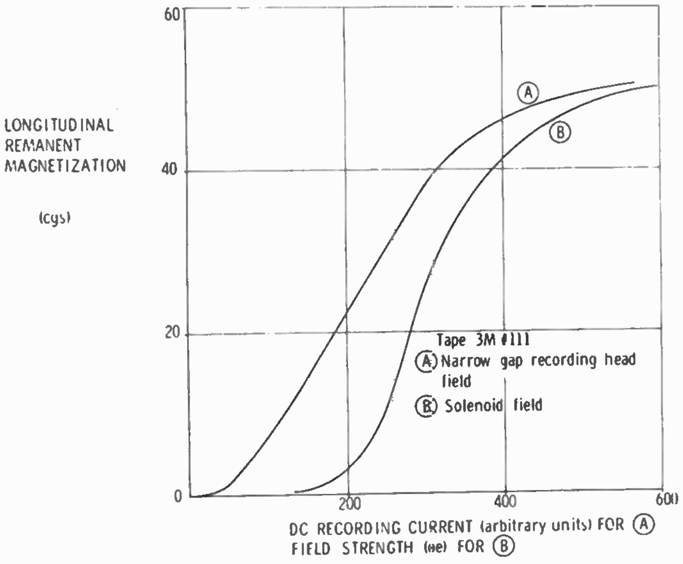


Fig. 2—Remanent magnetization vs dc field.

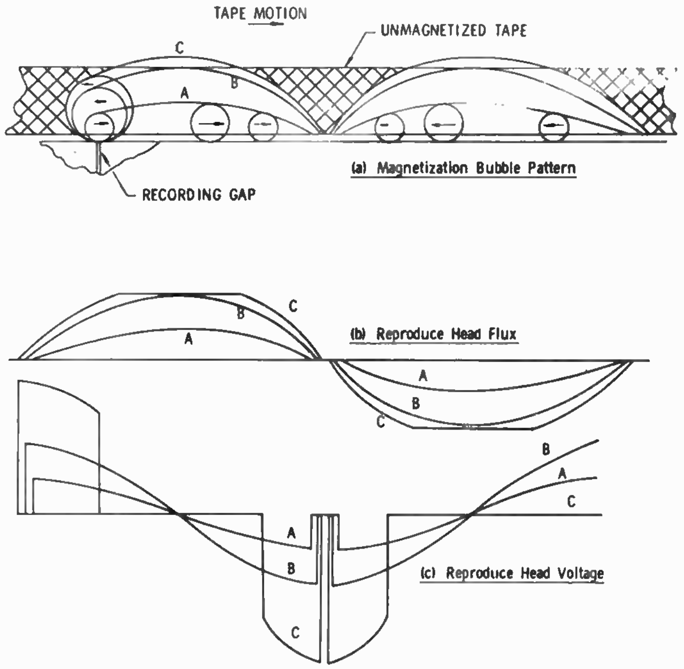


Fig. 3—Long wavelength recording without bias.

## ZERO BIAS RECORDING

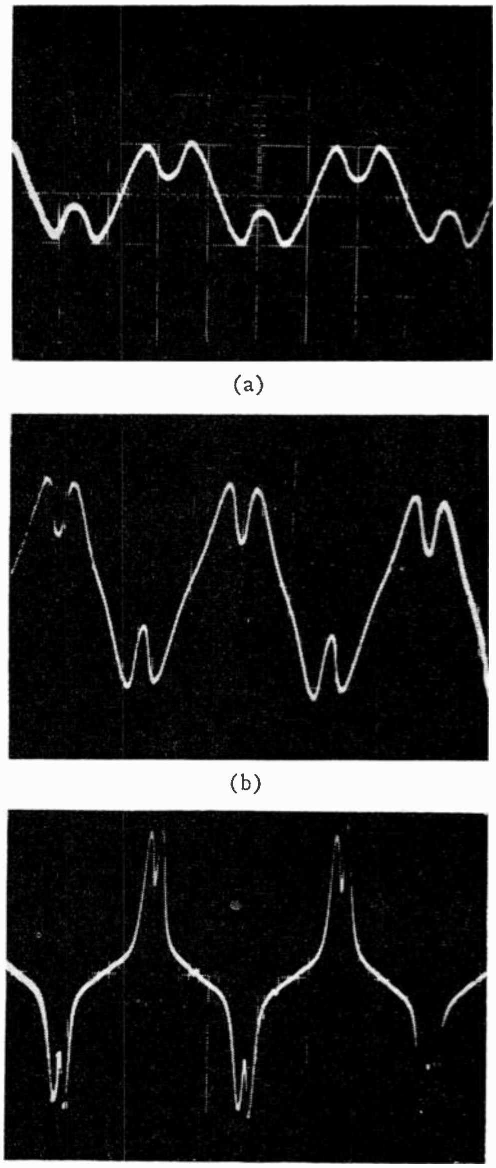
Using the picture of the magnetization bubble whose diameter is proportional to the signal, the process of recording can be described in geometrical terms by considering the growth and decay of the bubbles, following the signal variations, and the corresponding magnetization pattern imprinted on a magnetic coating moving through the bubbles.

The simplest recording condition occurs when an alternating signal whose amplitude variation is small during the passage of a tape element across the recording bubble is applied to the recording head without bias. The magnetization bubble pattern imprinted on the tape for a sinusoidal signal is shown in Fig. 3(a), in which the arcs indicate the magnetization boundaries. The three boundaries shown in Fig. 3 correspond to signal magnetization bubbles whose maximum diameters are less than, equal to, and greater than the coating thickness for curves A, B and C, respectively. Thus, direct recording of a sinusoidal signal whose wavelength on the tape is long compared to the coating thickness, is essentially variable depth magnetization following the signal amplitude until the bubble diameter becomes equal to the tape thickness [curve B, Fig. 3(a)]. For larger signals, the recording bubble penetrates beyond the remote side of the tape coating and further magnetization is obtained by the recorded bubbles becoming steeper sided and pushing into the unmagnetized tape area indicated in Fig. 3(a). Eventually the recorded bubbles will have initially perpendicular sides when the diameter of the bubble $R_c$ is equal to $\lambda/\pi$, where $\lambda$ is the wavelength of the recording on the tape. However, for long wavelengths, this condition corresponds to a magnetization bubble whose diameter is large compared to the coating thickness and for which it is no longer valid to ignore the vertical component of magnetization. As indicated in Fig. 3(a), due to imperfect contact between tape and head, a finite magnetization bubble must be created before tape magnetization occurs. In practice, the recording field from a finite gap will also depart from that assumed for the model necessitating a finite recording current to produce a bubble of zero diameter. Referring to Fig. 2, the head current required to start magnetization of the tape is about 15 per cent of that required to magnetize right through the coating thickness. For a long wavelength recording, assuming the flux through the reproducing head is proportional to the thickness of the magnetized layer, the replay head flux is as shown in Fig. 3(b) correspond- to the three recording levels depicted in Fig. 3(a). The replay head voltages are shown in Fig. 3(c). It can be seen that, for long wavelengths, the distortions predicted are similar to those found in practice [Fig. 4 (a)–(c)].

The condition in Fig. 4(b) corresponds with the calculated maximum bubble diameter approximately equal to the coating thickness, by substituting in (4) measured values of ampere turns and coating coercivity.

## DC BIAS RECORDING

In the previous section it was shown that the recorded magnetization follows the signal applied to the recording head provided it is greater than a critical value required to produce a recording bubble of zero diameter and smaller than that for a bubble diameter equal to the tape thickness. The first requirement may be overcome by applying a bias current with the signal current in such a form that it is not reproduced in playback, yet allowing signal recording to take place inside the tape layer where the recorded magnetization changes are proportional to changes of signal current applied to the record head. Another way of looking at the


(a)

(b)

(c)

Fig. 4—Zero bias recording, sinusoidal recording signal increasing (a) through (c).

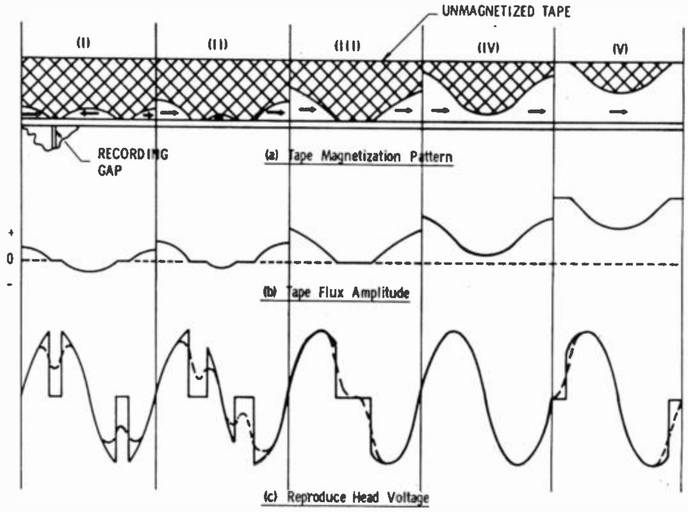
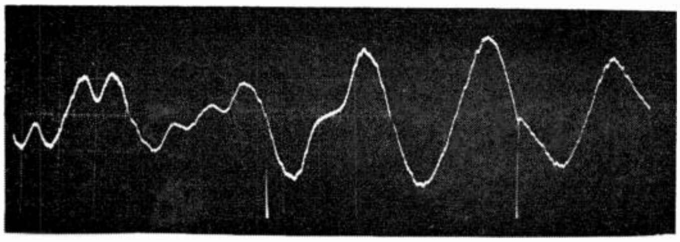


Fig. 5—DC bias recording model.


(a) (b) (c) (d) (e)
Unmagnetized Tape

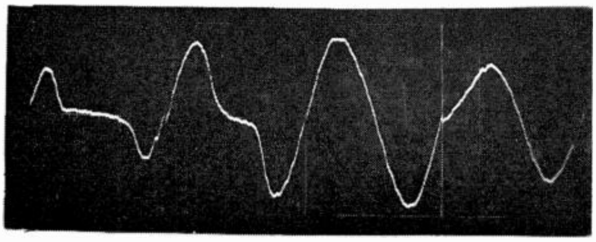

(f) (g) (h) (i)
Premagnetized Tape (Gain Reduced)

Fig. 6—DC bias recording.

bias function is that it moves the zero signal boundary from outside to inside the coating.

In the dc biasing method, a bubble of constant diameter equal to approximately half the coating thickness is created, which causes a layer of equivalent depth of tape to be magnetized in one direction. If signal is added to this bias, a depth modulation will result which corresponds to the signal field. Thus, magnetic poles will be generated along the boundary with a density proportional to the rate of change of the signal. Fig. 5(a) shows the depth modulation for a constant ac signal and dc bias increasing from zero in five steps to a value sufficient to push the signal modulation through to the remote side of the coating. Fig. 5(b) shows the corresponding longitudinal tape flux pattern and Fig. 5(c) the reproduce head voltage, assuming this is the differential of the tape flux amplitude. The dotted lines in Fig. 5(c) indicate the waveforms found in practice. Examples of the corresponding reproduce head waveforms are shown in Fig. 6(a)–(e). If the tape was previously saturated in the opposite direction to the bias field direction, then the pole density and reproduce head output voltage are doubled. Since the tape is premagnetized, it is not possible to obtain magnetization patterns of the type shown in columns i and ii of Fig. 5(a), which contain two magnetization directions. Instead, the zero bias pattern is similar to that of column iii. The experimental reproduce head waveforms for increasing dc bias on premagnetized tape are shown in Fig. 6(f)–(i).

It can be seen from Fig. 5(a) that the maximum undistorted signal may be recorded when the bias level is adjusted for the bubble diameter to be half the coating thickness as in Fig. 5(a), column iv. As would be expected from the model, the distortion is much more evident for large signal levels. When short wavelengths are recorded with dc bias, the separation between the magnetization boundary and the surface of the tape causes increased loss of replay head flux. This may be retrieved by reducing the dc bias and bringing the boundary nearer to the tape surface, with consequent loss of undistorted dynamic range.

### AC Bias Recording

The magnetization bubble concept can be extended to illustrate the mechanism of ac bias recording in which the signal current is added to a high-frequency bias current in the record head winding. The frequency of alternation of the signal current is small compared to the bias frequency, and the signal level is considered constant during the time of one bias cycle. Recording under such conditions is then pictured as a succession of magnetization "shells" created by oppositely polarized bubbles along the length of the tape having maximum diameters corresponding to the algebraic sum of the maximum ac bias field and the signal field. In the absence of a signal field, the ac bias field creates equal-size shells yielding a zero resultant magnetization. This process is illustrated in Fig. 7(a) where the bias amplitude is such as to create magnetization bubbles of diameter equal to the tape thickness. It will be shown later that this condition approaches that of optimum ac bias giving maximum magnetization for a constant signal. The relative dimensions in Fig. 7(a) correspond to a bias frequency of 100-kc tape speed 3.75 ips, and tape thickness $0.3\times10^{-3}$ inch. In a previous unpublished work,[8] the concept of magnetization bubbles has been used to arrive at a similar conclusion.

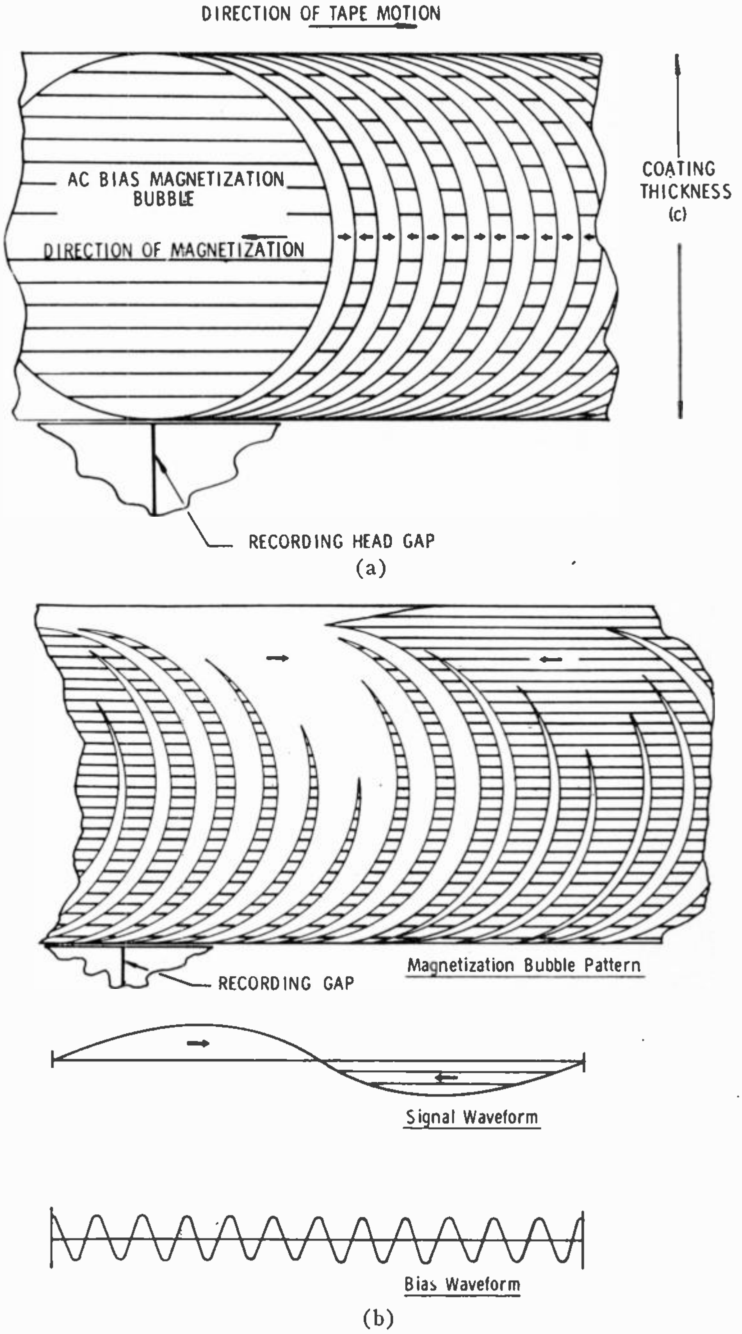


Fig. 7—AC bias recording. (a) Zero signal, (b) Long wavelength signal.

When a signal is superimposed on the ac bias, the bubbles corresponding to successive half cycles of bias increase or decrease in cross-sectional area, depending on whether the signal aids or opposes the bias. Thus, for particles of a given coercivity, there will be a net increase in the number of particles magnetized in the signal field direction proportional to the change in area of coating magnetized in the field direction if the magnetization inside the bubble can be considered uniform. If the change in radius of the bias bubbles due to the signal is $\Delta r$, then the area change is approximately $\pi r\Delta r$ for the recorded shells. Hence, the magnetization change is proportional to the signal change provided the bubble diameter is not greater than the coating thickness. The recorded bubble pattern for a small low-frequency signal superimposed on a high-frequency bias is shown in Fig. 7(b). It can be seen that areas of tape are magnetized over-all in the same direction as the signal and that these areas increase from the remote side of the tape as the signal increases. The near side of the tape is virtually demagnetized by the ac bias. There also appears a lag between these magnetized areas and the signal which increases with signal strength to a maximum value equal to the radius of the bias recording bubble. Thus, as in the case of dc recording, the region of tape responding to the signal is separated from the tape surface and improved short wavelength response will result from a decrease of bias level. However, since large fields are required for ac biasing, the vertical component of the field will be considerable, and extremely detailed analyses of the patterns of Fig. 7(b) are not valid. It is more true to think of the recorded patterns shown as a portrayal of a specific possible type of recorded pattern.

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[8] W. F. Brown, "The Magnetic Recording Process," 3M Internal Rept.; August, 1956.

### *Output vs Bias Amplitude*

According to the recording bubble concept described, the magnetization acquired due to adding a small dc signal to the ac bias can be calculated by considering the net change in area of the positive and negative shells due to adding or subtracting the dc and ac components of the resultant field. Two factors will affect the resultant change in average magnetization of the tape. The first, considered here, is the dependence of area change on the diameter of the bubble. The second factor, considered in the next section, is the dependence of the mean magnetization on the longitudinal separation of the recording bubbles, *i.e.*, the bias wavelength.

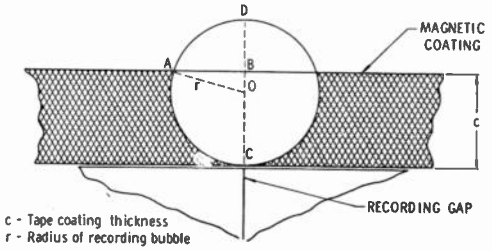

Fig. 8—Single recording bubble due to infinitely small recording gap.

The area of tape affected by a single bubble is illustrated in Fig. 8. When the bubble diameter is less than the coating thickness, the change in area due to a small signal $\Delta r$ is $2\pi r\Delta r$. The change of effective magnetization, being the magnetization per particle times the number of particles magnetized in the field direction, is proportional to $\pi r\Delta r$ for the series of overlapping bubbles in Fig. 7(a). Thus, as long as $r \leq c/2$, the recorded magnetization due to $\Delta r$ is proportional to the ac bias amplitude for small dc signals and constant bias wavelength. When $r > c/2$ the recorded magnetization is given by

$$I_R = K\frac{dA}{dr}\cdot\Delta r, \tag{5}$$

$K$ being the constant of proportionality between the area and magnetization change, and $A$ = area $AOB$ + area $AOC$ (Fig. 8). It follows from an elementary calculation that

$$I_R = \left[(\pi - \cos^{-1}\{c/r - 1\}) - \left(\frac{2c}{r} - \frac{c^2}{r^2}\right)^{1/2}\right] r\cdot\Delta r\cdot K. \tag{6}$$

The predicted dependence of tape magnetization on bias amplitude ($I_R$ vs $r$) is given by the relationships described and is plotted in Fig. 9. It is seen that a linear increase of magnetization with bias amplitude occurs until the recording bubble diameter just equals the coating thickness. When the bubble diameter exceeds the coating thickness, a very rapid decrease of output occurs having approximately an inverse square power dependence on bias amplitude. Fig. 10 shows an experimental curve (curve B) of longitudinal recorded magnetization vs bias amplitude for a small dc signal in good agreement with the calculated curve. However, quantitative comparison could only be made in the case of recording and playback if correction were made for the finite length of the recording gap, the perpendicular component of the recording field and the finite signal to bias ratio. For instance, curve A of Fig. 10 shows the output vs bias curve for a small long wavelength signal ($\lambda = 37$ mil) and similar bias conditions to curve B. The larger relative output at high bias values is due to the increased perpendicular component of the magnetization to which the reproducing head is sensitive. Thus, the assumption of longitudinal magnetization is a reasonable one only for magnetization bubbles not greater than the coating thickness.

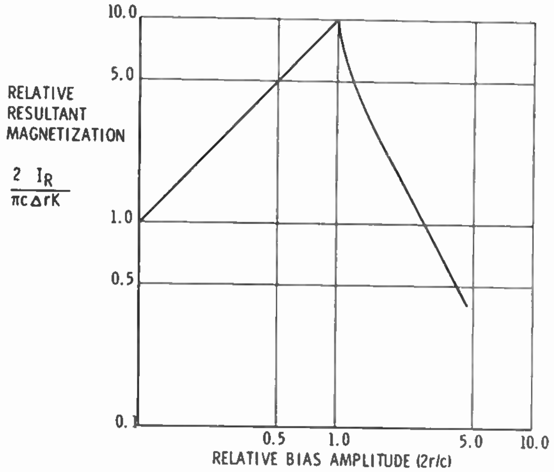

Fig. 9—Theoretical magnetization vs bias amplitude for small signals.

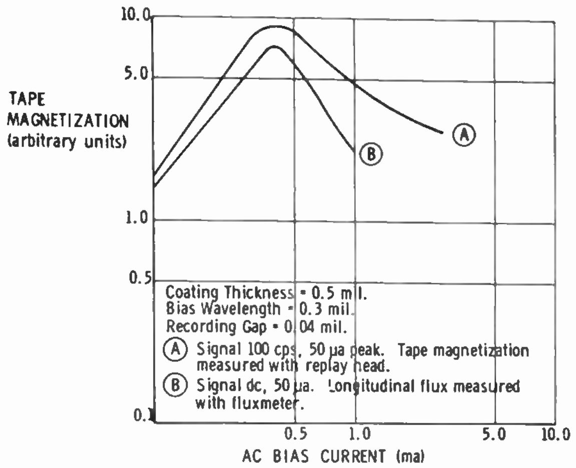

Fig. 10—Recorded magnetization due to small signal field vs ac bias amplitude.

### *Output vs Bias Wavelength*

The overlap of adjacent ac bias magnetization bubbles gives rise to a dependence of resultant magnetization on the bias wavelength. As the latter is increased,

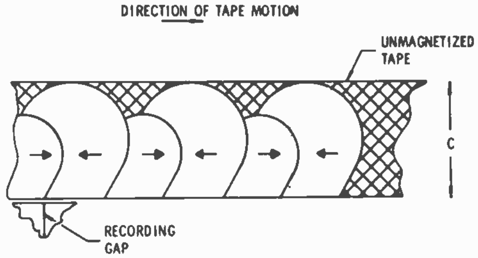

Fig. 11—Recorded bubbles due to large dc signal superimposed on ac bias.

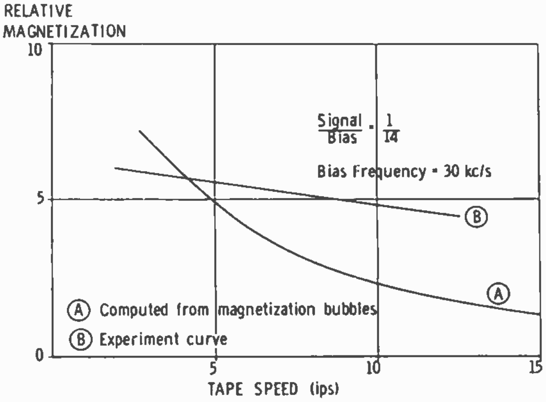

Fig. 12—Magnetization vs tape speed.

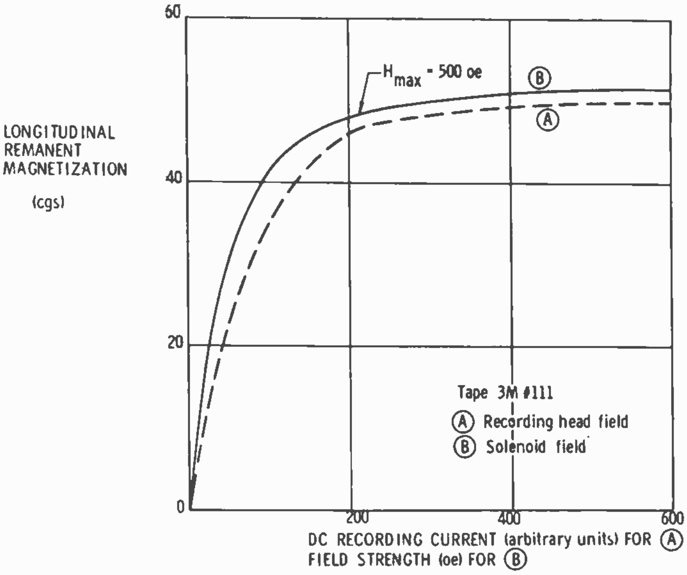

Fig. 13—Anhysteretic remanent magnetization.

the alternate bubbles, for which the bias and signal fields aid, overlap a smaller proportion of the preceding bubbles for which bias and signal oppose, and reduced magnetization occurs. For instance, considering the example at the beginning of this section, with a tape speed of 3.75 ips, bias frequency 100 kc and coating thickness $0.3 \times 10^{-3}$ inch, the large bubbles (signal and bias aiding) completely overlap the small bubbles for a signal to bias ratio of 1:6. Increase of tape speed or reduction of bias frequency would lead to reduced overlap of adjacent bubbles. In this way, the pattern in Fig. 11 corresponds to a bias frequency of 60 kc at 15 ips tape speed. Graphical computation of the relative mganetization for a practical signal to bias ratio (1:14) is shown in Fig. 12, curve A. The corresponding experimental curve B shows a wavelength dependence of sensitivity much smaller than predicted. The nonuniform magnetization inside the bubble may account for some of this discrepancy. In addition, the change in sensitivity due to overlapping bubbles may well be masked by the low anhysteretic susceptibility of tape materials. At this stage it is necessary then to invoke the effects of particle interaction on recording sensitivity. The inability of the simple model to explain fully the effects of bias wavelength on recording sensitivity is probably due to the gradual fall-off of magnetization at the edge of the bubble. Nonuniform magnetization is to be expected inside the bubble due to self-demagnetization fields of the cylindrical magnet so formed. Even more important would be the spread of critical fields due to internal fields acting on the particles. Fig. 13 shows the longitudinal anhysteretic remanent magnetization curves acquired when recording using optimum bias and a narrow gap record head (Curve A). Curve B shows the corresponding curve for simulated recording (ac and dc falling together) in a uniform field. The close correspondence between the shapes of these curves indicates that the controlling mechanism for magnetization acquisition exists in the anhysteretic magnetization process. In terms of magnetization bubbles, a spread of critical fields due to internal fields infers that a range of corresponding bubble diameters must be considered. At this stage a limit is reached in the usefulness of the present model.

## CONCLUSIONS

The model considered is capable of illustrating many magnetic recording phenomena under a variety of recording conditions. It serves as an initial introduction to the mechanism of tape recording, and it has the advantage of taking into account the geometrical properties of the recording field as well as the elementary magnetic properties of the materials used. The use of the model to illustrate zero and dc bias recording phenomena leads to a clear picture of the resulting tape magnetization pattern. The model is also applicable to an elementary portrayal of ac bias recording but the simplifications assumed impose limitations on good quantitative agreement with experimental results. Further detailed study of recording effects would necessitate introduction of the practical properties of tape coatings and record head fields. In particular, the assumption of longitudinal magnetization inhibits the applicability of the model to large applied field effects. The more difficult problem of analyzing short wavelength recording properties would also require account to be taken of the wavelength dependent properties of the reproducing process.

# Analysis of the Recording of Sine Waves*

IRVING STEIN†

*Summary*—Magnetic recording of the sine waves of all wavelengths is analyzed. The analysis shows that the recording process consists of two types of phenomena: 1) a virtual input scanning—the remanant tape magnetization (the recording point) appears at the front gap edge and moves over the gap towards the rear gap edge each half period. Thus, the tape is magnetically "scanned" by the input gap field in the direction opposite the tape motion. 2) A particular type of interference—as the half wavelength of tape passes over the gap, the input field will generally reverse polarity at least once. Thus, the different "scannings" on the same tape section will interfere with each other timewise. The net effect of these processes, even with the initial magnetization curve linear, is to produce a distorted tape magnetization output. The results clearly indicate that for longer wavelengths there is the greatest amount of distortion, but no amplitude attenuation or phase shift. Furthermore, in this wavelength region the recording is done over the entire gap. For smaller wavelengths, the reverse holds true; that is, there is a decreasing amount of distortion and an increasing attenuation and phase shifting. Also, the shorter the wavelength, the closer to the front gap edge is the recording point. It is also found that there is a theoretical lower limit to the wavelength that can be recorded and that at very short wavelengths the shape of the gap trailing field becomes most significant. The fact that increasing oversaturation at the shorter wavelengths decreases instead of increases the net tape magnetization is also explained.

## INTRODUCTION

### *Purposes*

THIS paper is an analysis of the unbiased recording of the longitudinal component of a sinusoidal input. Two general purposes are achieved here:

1) Within the approximations made, a fairly detailed picture is derived of the tape remanent magnetization processes, as it passes through the recording gap field.

2) A semiquantitative determination is made of the tape magnetization amplitude, phase, and distortion as a function of wavelength, gap width, spacing, and other relevant variables.

### *Method of Solution*

The general problem is sufficiently complicated to make any attempt at an exact analysis impracticable. The problem is, therefore, approached by solving first the problem of an idealized, or basic, model. The idealized model is based essentially on:

1) A gap fringing field which is zero outside the gap and smoothly reaches a maximum at the gap centerline. The field is taken as independent of $y$-spacing to the head.

2) Hysteresis ($M$-$H$) loops which are simple parallelograms.

This basic model presents both a qualitative picture of the basic magnetization processes involved and a basis for solution of the actual situation. The application of the basic model solution to the graphical representation of the gap fringing field results in a semiquantitative solution of the actual situation.

### *Basic Phenomena of Recording*

The analysis shows that the recording process consists of two types of phenomena:

1) A virtual input scanning: The remanent tape magnetization—the recording point—appears at the front gap edge and moves over the gap towards the rear gap edge each half-period. Thus, the tape is magnetically "scanned" by the input gap field in a direction opposite to tape motion.

2) A particular type of interference: As a half-wavelength of tape passes over the gap, the input field will generally reverse polarity at least once. Thus, the different "scannings" on the same tape section will interfere with each other, timewise. Although both phenomena coexist generally at all wavelengths, scanning is more important at longer wavelengths and interference at shorter wavelengths. The net effect of these two processes, even with a linear virgin magnetization curve, is to produce a distorted tape magnetization output.

These two basic processes are quite general and their existence depends only on very general assumptions made about the nature of the gap fringing field.

### *Some Results of the Idealized Model*[1]

For the idealized model, we conclude:

1) For long wavelengths ($\lambda \gg l$) the output distortion does not depend to any great extent on the $M$-$H$ loops or fringing field shape. The most important parameters here are $g(\equiv \lambda/2l)$, and the shape of the initial magnetization curve. The effect of a nonlinear initial magnetization curve can be shown to be approximately equivalent to a change in $g$.

2) For $g \geqq 1$ there is no amplitude attenuation or phase shift, only wave shape distortion. The recording is done over the entire gap.

3) For $g < 1$ there is not only distortion but also amplitude attenuation and phase shift. As $g$ gets smaller, the effective recording takes place in a region closer to the front gap edge.

4) For $g \ll 1$ it is found that the significant aspects of the fringing field in the determination of the the tape magnetization are the slope of the field at the leading

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† Ampex Corp., Redwood City, Calif.

[1] Definitions of symbols are tabulated at the end of the paper.

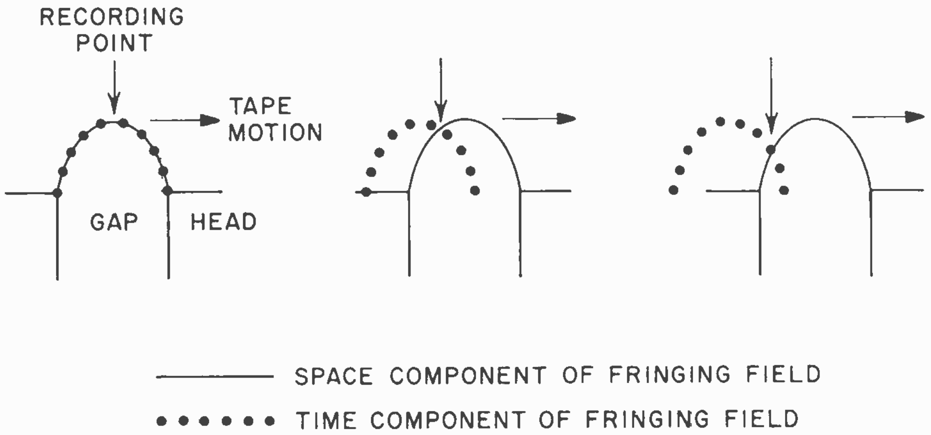

Fig. 1—Basic model of gap-fringing field.

edge of the gap and the magnitude of the trailing field. In this wavelength region the shape of the hysteresis curves is not of first importance.

### *Application to the Actual Situation*

The effective gap width, and thus the effective $g(\equiv g_e)$ is actually a function of spacing to the head, wavelength, and, to some extent, field shape. The analytical approach is to express the effect of all these variables in terms of $g_e = \lambda/2l'$, where $l'$ is the effective gap width. ("Effective gap width" means the gap region over which the field is effective as a magnetic source relative to the tape.) The tape magnetization distortion, attenuation, and phase change is then, through $g_e$, a function of all relevant variables such as those previously mentioned.

## ANALYSIS BASED UPON IDEALIZED MODEL

### *Definition of Idealized Model*

The basic model of the recording process is ideal in two respects: the form of the gap fringing field and the form of the *M-H* (hysteresis) loops.

1) The strength of the gap fringing field is taken to be 180° of a cosine function over the gap, and zero outside the gap. The field is not assumed to vary with spacing from the head (Fig. 1). Thus,

$$H = H_0 a(t) \cos \frac{\pi x}{l},$$

where $x = 0$ at the gap center-line. If the input $a(t)$ is sinusoidal, then

$$H = H_0 \cos \frac{\pi x}{l} \cos 2\pi \text{ft}.$$

2) In order to determine the remanence on the tape as a result of the applied gap field it is necessary to assume an *M-H* model. A particularly simple one was chosen, *i.e.*, an idealized model. Here the *M-H* loops are parallelograms where the sides of the various loops are parallel to each other. The virgin magnetization curve is taken (at first) as a straight line, starting from $M = H = 0$ with a slope $k$ (Fig. 2). The magnetization, as a result of sequentially applied maximum fields, $H_i$, is simply the summation of $n$ magnetizations; namely,

$$M_{m,n} = M_1 - 2 \sum_{i=2}^{m \leq n} (-1)^i M_i$$
$$= \pm k \left[ |H_i| - 2 \sum_{i=2}^{m \leq n} (-1)^i |H_i| \right],$$

where $m$ is the total number of sequentially applied fields, and $n$ is the maximum value $m$ can achieve. This equation is subject to the condition $|H_i| \leqq |H_{i-1}|$ for all $i$. If $|H_i| \geqq |H_{i-1}|$ for all $i$, then $M_{m,n} = kH_m$. Thus, for $n = 2$, we have

$$M_{1,2} = kH_1$$
$$M_{2,2} = \pm k[|H_1| - 2|H_2|] \qquad |H_2| \leqq |H_1|$$
$$M_{2,2} = kH_2 \qquad |H_2| \geqq |H_1|.$$

This equation merely states that the net magnetization results from a simple, linear superposition of the alternating magnetic fields.

At first the virgin magnetization curve is taken as a constant slope line in order to determine whether tape magnetization distortion is due to factors other than a nonlinear magnetization curve. It will be found that distortion is inherent in the nature of gap recording and can be either increased or decreased by a nonlinear magnetization curve.

### *Magnetization for a Single Field Polarity*

As a first step in the analysis we wish to find $M_1$, which is the magnetization resulting from the application of a single field polarity. If $X_1$ is the distance the tape has moved in time $t$ with a velocity $v$, and $x$ is the distance from the gap centerline, then $x_0 = x + x_1$ is a point on the tape a distance $x_0$ from the tape coordinate origin (Fig. 3).

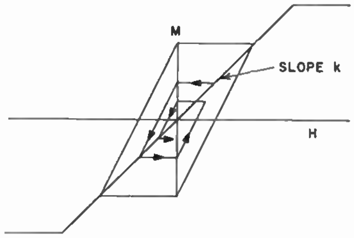

Fig. 2—Assumed hysteresis loops.

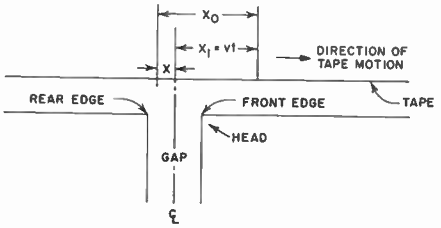

Fig. 3—Tape and space coordinate system.

Since $ft = vt/\lambda = x_1/\lambda$, the previous equation for $H$ can now be written as

$$H = H_0 \cos\left(\frac{\pi x}{l}\right) \cos \frac{2\pi}{\lambda}(x_0 - x)$$
$$= H_0 \cos(gs) \cos(s_0 - s),$$

where

$$s \equiv \frac{2\pi}{\lambda} x, \qquad s_0 \equiv \frac{2\pi}{\lambda} x_0, \qquad g \equiv \frac{\lambda}{2l},$$

and

$$M = kH_0 \cos(gs) \cos(s_0 - s).$$

It is necessary to determine the maximum $M(\equiv M_1)$ for a given polarity. Thus, by setting $dM/dx = 0$, we get

$$g \tan(gs) = \tan(s_0 - s).$$

This equation determines $s = s(s_0)$ and

$$M_1 = kH_0 \cos[gs(s_0)] \cos[s_0 - s(s_0)]$$

giving the maximum remanence as a function of the tape coordinate $s_0$. Thus, the maximum remanence does not generally occur at the gap centerline or some fixed distance, $s$, from it but is generally a function of the phase of the input signal, *i.e.*, $s = s(s_0)$, arising from the fact that that the tape magnetization is a function of both $x$ and $t$. For instance, for $g = 1$, $s = s_0/2$. Thus, the recording point distance $s$ increases with the distance the tape moves, $s_0$. This shifting of the recording point starts at the gap front edge and moves toward the rear edge, whereupon it then repeats itself. Thus, the motion of the "scanning" is always in a direction opposite to that of the tape. The average "scanning" velocity is

$$v' = v\left(1 + \frac{1}{g}\right).$$

### *Analysis for $g \geqq 1$*

Since the "scanned" length each half-period is larger than $\lambda/2$, there is a section of each half-wavelength of tape, $\lambda/2g = l$, which is recorded upon more than once. Thus, for all $g$, some part of a half-wavelength on the tape receives at least two magnetizations. Generally, the number of "scannings" is $n = 1 + 1/g$. These consecutive "scannings" form an interference pattern over each half-wavelength (Fig. 4).

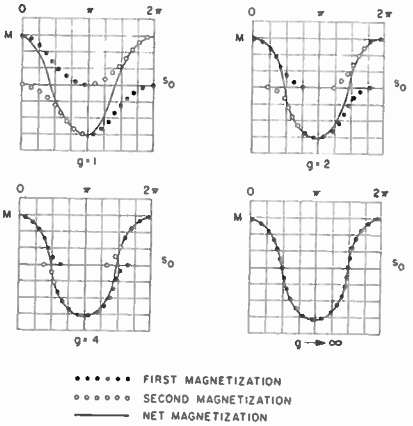

Fig. 4—Output wave shapes for $g \geqq 1$.

For $g \geqq 1$, the magnetizations are

$$M_{1,2} = kH = kH_0 \cos(gs) \cos s \qquad 0 \leqq s_0 \leqq \frac{\pi}{2}\left(1 - \frac{1}{g}\right)$$

$$M_{2,2} = k[|H_1| - 2|H_2|] \qquad \frac{\pi}{2}\left(1 - \frac{1}{g}\right) \leqq s_0 \leqq \frac{\pi}{2}$$

$$= kH_0[\cos(gs) \cos s_1 - 2 \sin g(s - \bar{s}) \sin(s_1 - \bar{s}_1)]$$

$$s_2, \bar{s}_1 \text{ determined at } y_0 = \frac{\pi}{2}\left(1 - \frac{1}{g}\right)$$

$$M_{2,2} = kH_2$$

$$= -kH_0 \sin g(s - \bar{s}) \sin(s_1 - \bar{s}_1) \qquad \frac{\pi}{2} \leqq s_0 \leqq \pi$$

with the subsidiary equations

$$g \tan(gs) = \tan s_1$$
$$s_0 = s + s_1.$$

For $g < 1$, a similar set of magnetization curves is obtained. [*Note:* $H_i$ is the $i$th magnetizing field, and $M_i$ is the $i$th recording (magnetization, induction, remanence). Thus, $M_i$ is not the *net* induction on the tape, but an extra remanence due to the $i$th field.]

If $M_{1,2}$ and $M_{2,2}$ are extended into each other's region as shown in Fig. 5, there is no change in the net magnetization. For $g = 1$, the curves for $M_{1,2}$, $M_{2,2}$ are seen to be sinusoidal plus a constant component. For $g \to \infty$ the curves become one and are purely sinusoidal. For in-between values of $g$, harmonics of the basic frequency

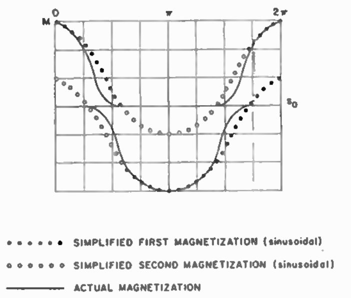

Fig. 5—Relationship of the simplified to the actual magnetization curves.

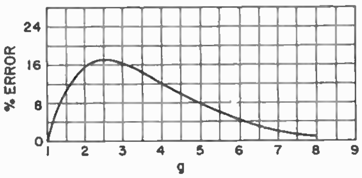

Fig. 6—Estimated average deviation of simplified curve from exact curve.

are present. By omitting the harmonics from these extended magnetization curves, we introduce at most an error of about 18 per cent (in the region of $g=2$), decreasing the net distortion (Fig. 6). Thus, for $g \geqq 1$, the magnetization curves are approximately

$$M_1 = kH_0 \left[ \frac{\sin \frac{\pi}{2g} + \cos s_0}{1 + \sin \frac{\pi}{2g}} \right]$$

$$M_2 = -kH_0 \left[ \frac{\sin \frac{\pi}{2g} - \cos s_0}{1 + \sin \frac{\pi}{2g}} \right].$$

The net magnetization, therefore, is the result of the interference of two identical out-of-phase magnetization curves.

The Fourier coefficients of the recorded magnetization based upon these magnetization curves are

$$\frac{\pi}{2kH_0} a_{2n-1} = \frac{(-1)^{n+1}}{1 + \sin \frac{\pi}{2g}} \left[ \frac{2 \sin \frac{\pi}{2g} \cos \left( \frac{2n-1}{2g} \right) \pi}{2n-1} + \frac{\frac{\sin \pi(n-1)}{g}}{2(n-1)} - \frac{\sin \frac{n\pi}{g}}{2n} \right], \quad n \neq 1$$

$$\frac{\pi a_1}{2kH_0} = \frac{\sin \frac{\pi}{g} + \pi \left( 1 + \frac{1}{g} \right)}{2 \left( 1 + \sin \frac{\pi}{2g} \right)}$$

$$\frac{\pi}{2kH_0} b_{2n-1} = \frac{-(-1)^n}{1 + \sin \frac{\pi}{2g}} \left[ \frac{2 \sin \frac{\pi}{2g} \cos \left( \frac{2n-1}{2g} \right) \pi}{2n-1} + \frac{\sin^2 \frac{(n-1)\pi}{2g}}{n-1} - \frac{\sin^2 \frac{\pi n}{2g}}{n} \right], \quad n \neq 1$$

$$\frac{\pi b_1}{2kH_0} = \frac{-\sin^2 \frac{\pi}{2g}}{1 + \sin \frac{\pi}{2g}}.$$

The magnetization is zero where $M_i = -2M_2$. This occurs at

$$\cos s_0 = \frac{1}{3} \sin \frac{\pi}{2g}.$$

For a measure of the harmonic distortion, consider the $M$ zero point, the third in-phase, and first out-of-phase harmonics (Fig. 7). For $g=1$, the zero $M$ is shifted 20° from a nondistorted $M$. The fundamental is phase-shifted 19° ahead of the net magnetization curve, and the out-of-phase Fourier components are given in Table I. All in-phase components except the fundamental are zero.

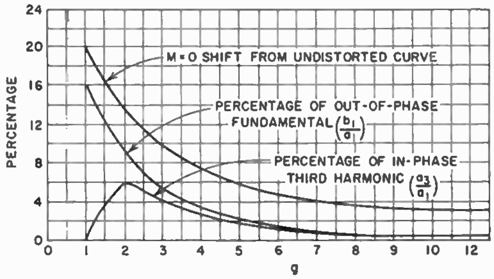

Fig. 7—Distortion characteristics as a function of $g$ for $g \geqq 1$.

TABLE I

| $n$ | 1 | 3 | 5 | 7 | 9 | $m$ |
|---|---|---|---|---|---|---|
| $b_n$ | $\frac{-1}{\pi}$ | $\frac{1.2}{3\pi}$ | $\frac{7}{5\pi}$ | $\frac{1}{7\pi}$ | $\frac{0.8}{9\pi}$ | $\frac{1}{m\pi}$ |

It is clear that distortion exists even for a linear virgin magnetization and is a function of $g$. This type of distortion, which results not from the interference of adjacent "bits," but instead occurs within one half-wavelength, is the kind that occurs also in pulse recording. In both cases there is a shift in the axis cross-over point [2].

### *Analysis for $g<1$*

For $g<1$ a procedure similar to that for $g \geqq 1$ is followed (Fig. 8). By extending the magnetization curves and taking only the constant and fundamental frequency we get, for the $p$th magnetization,

$$\frac{M_p}{kH_0} = \frac{(-1)^{p+1}}{1 + \sin \frac{\pi}{2g}} \cdot \left\{ \sin \frac{\pi g}{2} + \sin g \left[ (2s - 1) \frac{\pi}{2} - s_0 \right] \right\}.$$

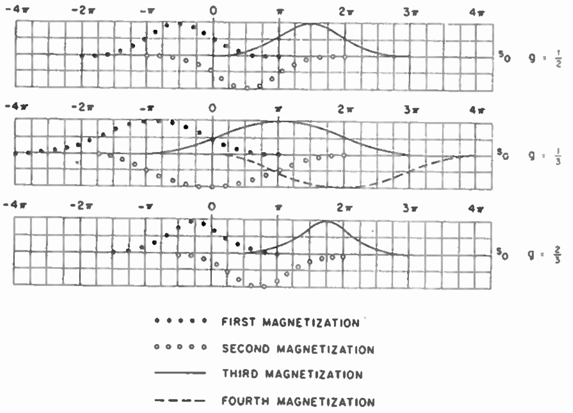

Fig. 8—Individual magnetization curve for $g<1$.

The net magnetization, resulting from the interference of many magnetizations, satisfies the required conditions for it to be

$$M_{m,n} = \pm k \left[ |H_r| - 2 \sum_{p=r+1}^{m} (-1)^p |H_p| \right].$$

$H_r$ is the "first significant" field; *i.e.*, it results in a $M_{r,n}$ larger than all previous $M_{r,n}$. Erasure effectively takes place before the "first significant" field. (As defined previously, $M_{m,n}$ designates the net induction after the $m$th recording where $g$ is such as to produce $n$ recordings altogether.) Thus, recording takes place only in the front half of the gap, *i.e.*, where the fringing field is decreasing relative to the tape motion.

The evaluation of the final magnetization $M_{n,n}$ for $n\,(=1+1/g)$ integral (each part of every $\lambda/2$ magnetized the same number of times) is

$$\frac{(-1)^{n+1}}{kH_0} M_{n,n} \left(1 + \sin \frac{\pi g}{2}\right) \cos \frac{\pi g}{2}$$
$$= \sin \frac{\pi g}{2} \cos \frac{\pi g}{2} + (-1) \frac{n-1}{2} \sin \frac{\pi g}{2} \sin g \left( \frac{\pi}{2} - s_0 \right).$$

A plot of the amplitude $M_{n,n}$ vs $g$ shows that $M_{n,n}$ generally decreases with decreasing $g$ except at $g=0.25$ where $M_{n,n}$ increases somewhat (Fig. 9).

The phase shift is $\phi = \pi[(1/g) - 1]$. Thus, as the wavelength decreases, the phase of the final recording increases. The actual recording point distance from the gap centerline is $\phi/2\pi(\lambda/2) = l/2(1-g)$. Thus, as $g$ decreases from 1 to 0, the final recording moves from the gap centerline to the front gap edge. These results, of course, will be modified by the actual gap field. The modified graphs are shown in Figs. 10 and 11.

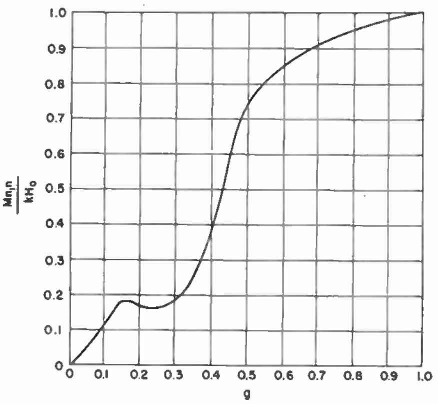

Fig. 9—Output magnetization as a function of $g$ (idealized model).

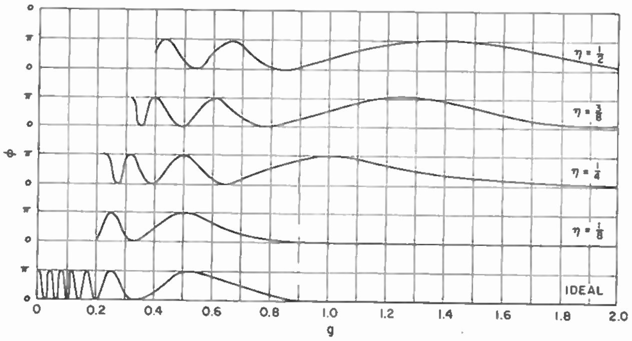

Fig. 10—Phase shift $\phi$ vs $g$ for various values of relative spacing $\eta$.

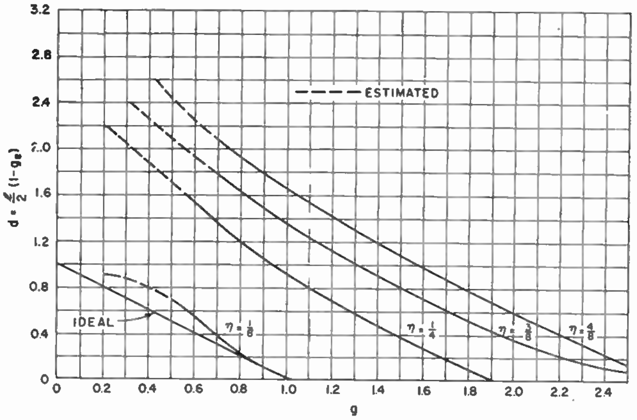

Fig. 11—Location (in $l/2$ units) of the recording point $d$ aft of the gap centerline where no further change in magnetization occurs vs $g$.

### *Effect of a Nonlinear Initial Magnetization Curve*

The actual virgin magnetization curve (between its toe and knee) is fairly close to a straight line. The susceptibility of the toe region is quite small. Therefore, we replace the assumed linear virgin magnetization curve by one having $M$ zero for $H \leqq H_a$ (the toe region) and $M = kH$ from then on up to the knee (Fig. 12). The effect of this change can be expressed as a change in $g$ (Fig. 13). If $a = H_a/H_0$, then the changed $g(\equiv g_0)$ is

$$g_0 = \frac{g}{1 - ga}\,.$$

The changed $M$ is

$$M = M_0(1 - ga).$$

Since, for $g_0 \geqq 1$, distortion decreases with increasing $g_0$, an increase in $a$ up to $a = 1/g$ will apparently reduce distortion. For $a > 1/g$, the familiar flattening of the magnetization curve in the region of the time axis begins to appear.

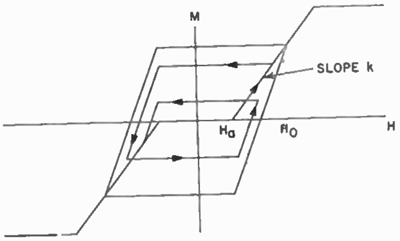

Fig. 12—Nonlinear initial magnetization curve.

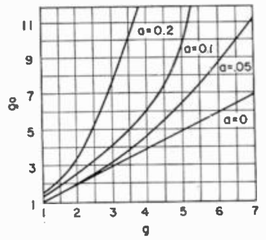

Fig. 13—Change in $g$ due to nonlinearity of initial magnetization curve.

## Application of Basic Analysis to the Actual Situation

### *Validity of M-H Loops*

The $M$-$H$ model assumed is a fair approximation to the actual $M$-$H$ loops for $\gamma - \mathrm{Fe_2O_3}$ [2], [6]. There appear to be two main differences: 1) the toe susceptibility is greater than zero; 2) the minor loops are not quite parallel and tend to rotate slightly as $H_{\max}$ decreases, causing a magnetization which is slightly less than that derived from the assumed model. The main effect of these two deviations is: 1) the distortion of a given wavelength is not evaluated at $g_0 = g/(1 - ga)$ but at some intermediate value between $g$ and $g/(1 - ga)$; and $M_{n,n}$ decreases with $g$ somewhat more rapidly than our calculation shows.

The assumed idealized gap fringing field, although giving a fairly adequate basis for a qualitative picture of the record process, gives quantitative results only in the limiting region of very thin tape oxide layer ($t \ll l$) and large $g (g \gg 1)$.

However, the analysis obtained using this model can be applied to the actual field. The actual field differs from the ideal in that it only grossly resembles a sinusoidal shape and varies in shape and strength with spacing to the head. (Spacing from the tape is sufficient to prevent "double" recording from taking place.) The decrease in field with spacing is shown in Fig. 14. The shape of the field for various spacings is shown in Fig. 15.

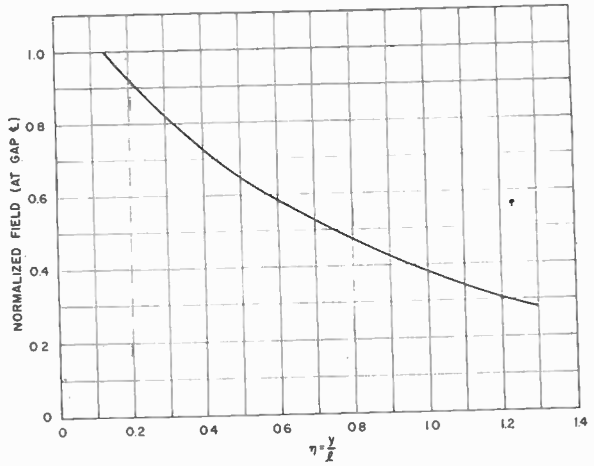

Fig. 14—Relative field strength at gap centerline ($M/KH_0$) vs relative spacing to the head ($\eta$).

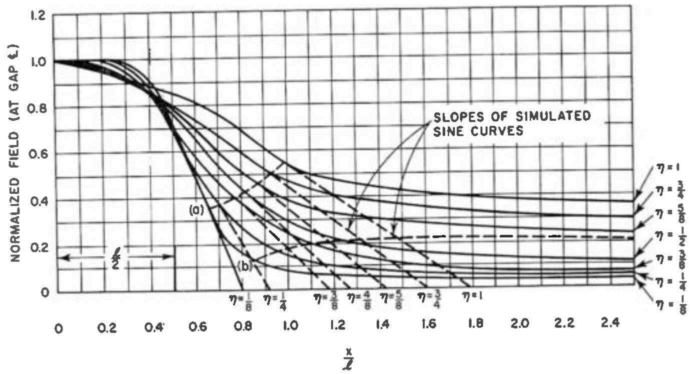

Fig. 15—Normalized gap magnetic field strength vs relative distance along the gap for various spacings.

### *Distortion from the Actual Gap Field ($g \geqq 1$)*

Close to the head, the fringing field is more uniform than sinusoidal. If the field were perfectly uniform across the gap, then for $g = 1$, the $M = 0$ point is 30° instead of 20° from a nondistorted $M$. The $M = 0$ point for a uniform gap field is determined from

$$\cos\left(\frac{2gs_0 - \pi}{2g - 1}\right) = 2 \sin\left[s_0 - \frac{\pi}{2}\left(1 - \frac{1}{g}\right)\right].$$

For the layers of tape spaced further away from the head, there are two compensating effects as far as the

$M=0$ point is concerned: 1) field form is more sinusoidal so the $M=0$ angle is less; 2) effective gap width, $l'$, is greater, making $g_e$ smaller, and thus increasing the $M=0$ angle. Generally speaking, therefore, for $g>1$ we expect not only distortion in the tape magnetization but some average magnetization curve which results from the varying distortions produced in different layers of tape. Making the reasonable assumption that the angle $\theta$ increases proportionately as we space out to $\eta=\frac{1}{2}$ from $\eta=\frac{1}{8}$, the actual location of $M=0$ is then estimated for different spacings as a function of $g$. This is shown in Fig. 16.

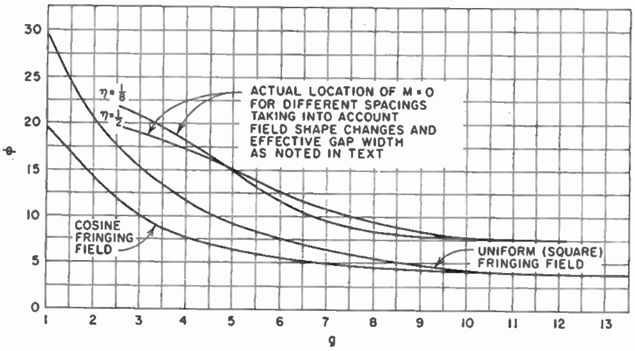

Fig. 16—Distortion for $g \geqq 1 : M=0$ displacement angle $\theta$ as a function of $g$.

### *Attenuation and Phase With the Actual Gap Field ($g<1$)*

The region $g \lesssim 1$ is a transition region and, therefore, the most difficult to deal with. The region $g \ll 1$ is probably the most important since it is in this region where the short wavelength limit, if any, exists. We can make a semiquantitative analysis of amplitude, phase, and short wavelength limit in this region.

The idealized analysis showed us that for $g<1$, there is effective erasing of the previous magnetization until the region of decreasing fringing field is reached. For small spacing from the head, the field is fairly uniform until it drops off sharply at the front gap edge. Thus. for $g \gg 1$, the effective $g$, $g_e$, might be even smaller than $g$. At further spacing from the tape, $l'$ increases, again making $g_e$ smaller than $g$. Fig. 22 is a plot of $g_e$ vs $g$ for various relative spacings. The effective magnetic gap width $l'$, as a function of spacing to the head, is estimated by attempting to simulate the actual field slope in the forward part of the gap by a sine wave slope. Neglecting the effect of the trailing field, which will be considered in the next section, the graphical approximation for different spacings to the head is shown in Figs. 17–19.

Figs. 20 and 21 give the relative magnetization as a function of $g$ for different spacings—the first for normalized, the second for actual field strengths. These graphs are derived from combining the information in Figs. 9, 22 and 23.

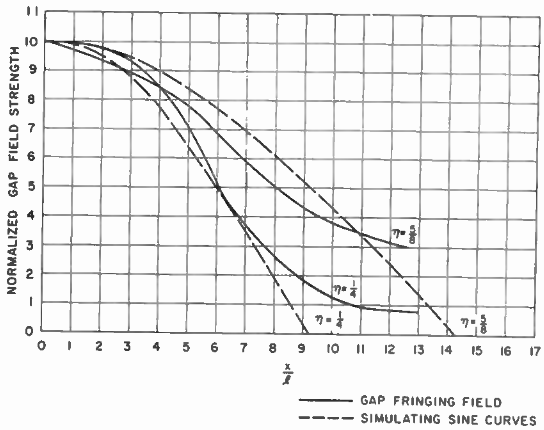

Fig. 17—Gap fringing field and simulating sine curves for $\eta=\frac{1}{4}$ and $\frac{5}{8}$.

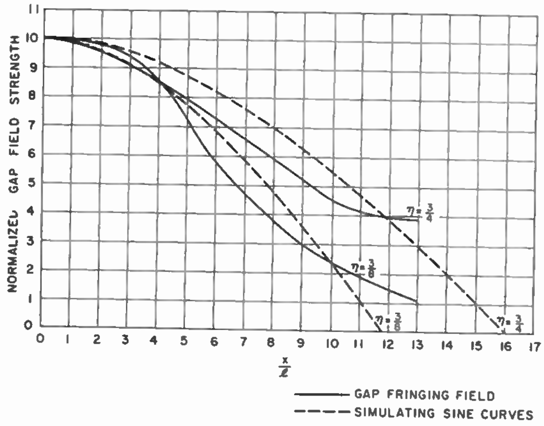

Fig. 18—Gap fringing field and simulating sine curves for $\eta=\frac{3}{8}$ and $\frac{3}{4}$.

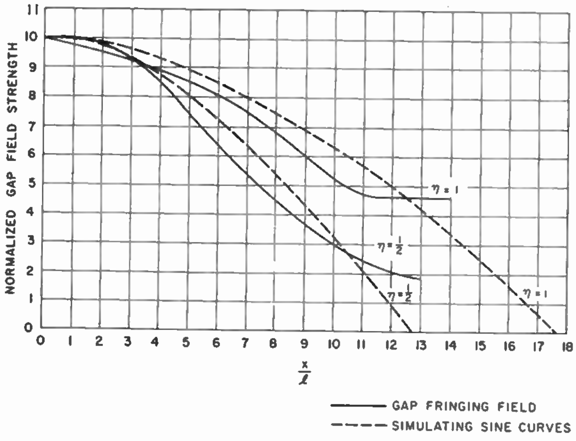

Fig. 19—Gap fringing field and simulating sine curves for $\eta=\frac{1}{2}$ and 1.

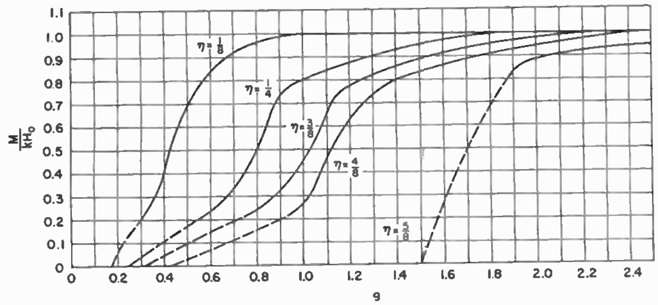

Fig. 20—Relative magnetizations for different spacings, assuming a fixed field strength along the gap centerline vs $g$.

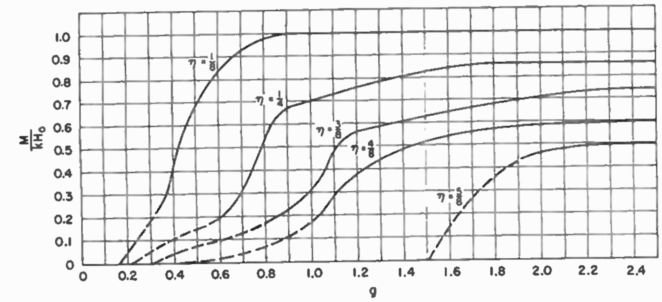

Fig. 21—Modification of Fig. 20, taking into account the decrease in actual field strength with increased spacing.

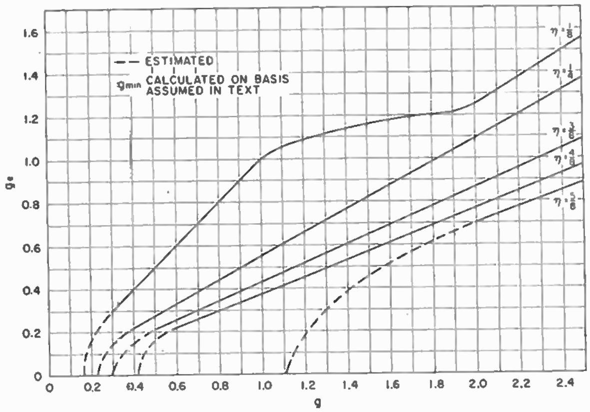

Fig. 22—$g_e$ vs $g$ for various values of relative spacing $\eta$.

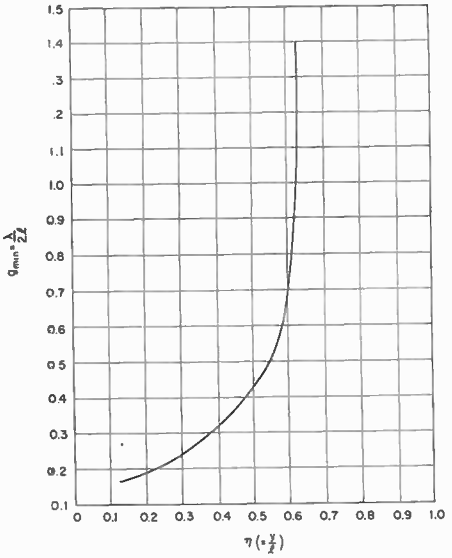

Fig. 23—Minimum recorded $g$ vs relative spacing $\eta$.

The final recording point for $g \ll 1$ is in the region of the front gap edge, especially for the layers of tape close to the head. Thus, the short and long wavelength amplitudes will tend to separate on the tape up to a distance $l'/2$, since for $g_e \geqq 1$ the final recording point is at the gap centerline. From Figs. 10 and 11, it can be seen that any momentary increase in head-to-tape spacing will result in not only a decreased tape magnetization, but also a phase shift in the recorded signal. This makes the problem of timing signals for $g < 1$ quite difficult, because a partial drop-out might record timing information incorrectly.

The wavelength separation and phase changes as shown in these figures also indicate the extreme difficulty in FM recording for $g < 1$. The use of an adequate thin film tape would increase resolution, but would hardly help in the timing problems resulting from drop-outs. Since $g_e$ is smaller for increased spacing, most of the recording will be done at the surface layers of tape. However, even in these surface layers the variation of $g_e$ and phase is significant.

### *Short Wavelength Limit*

The minimum $\lambda/2$ which is recordable is equal to the distance between the beginning of the trailing field and that point where the field strength is approximately one-half as much. These points are designated, respectively, (a) and (b) in Fig. 15. $G_{min}$ vs $\eta$ is plotted in Fig. 23.

It is apparent from Fig. 23 that as the tape is spaced $\eta > 0.6$, the minimum $g$ which can be recorded becomes considerably greater than 1. Therefore, for values of $g$ equal to or smaller than this, it is not possible to increase the tape magnetization by merely increasing the input coil current. The effective saturation field for the outer layers of the tape oxide is less than the inner layers, and is $g$-dependent. Thus there is, essentially, an effective susceptibility of the tape, $k_e$, which is a function of $g$ and $\eta$. It should be pointed out, however, that the variation from linearity of the $M$-$H$ loops will become significant here, and a more accurate representation of the hysteresis loops would be required to give any more than a qualitative picture.

### *Fields Above Saturation Level*

Even if the field becomes large enough to saturate a layer of the tape oxide, the magnetization of the layer is still a function of the input field. In single NRZ pulse recording, the distortion is a function of the field strength ($H>H_s$). In fact, not only is the location of the crossover of the step changed, but also the higher harmonics of the step function are attenuated. Thus, the magnetization amplitude is decreased and the shape is less square. On the other hand, if there is a train of bits of a high packing density, the analysis predicts that as $H>H_s$ increases, the amplitude at the tape outer layers will continue to rise until a maximum is reached, and will then begin to decrease. The peak amplitude will then be reached at smaller fields for larger frequencies. The general picture for an outer oxide layer is illustrated in Fig. 24.

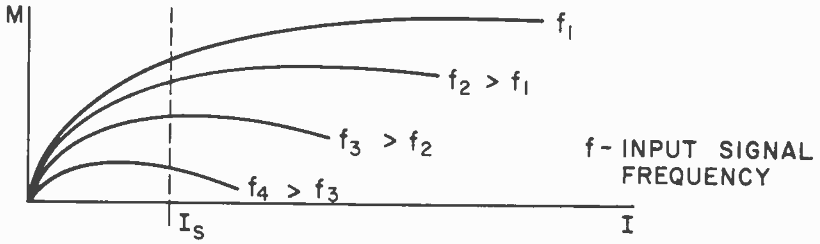

Fig. 24—Effect of a saturating input field on tape magnetization.

The explanation of this phenomenon in both single NRZ pulses and high packing density bits (or short wavelength sine waves) is the same—it arises from an interference of the adjacent bits of the higher frequency components of the signal with each other, resulting finally in a degree of self-erasure. Reference to Fig. 15 will show that for $\eta=1/8$, for example, as $H>H_s$ the slope of the fringing field becomes larger. Thus the effective gap width $l'$ will decrease resulting in a larger $g$ and less attenuation. Thus, even if there is no increase in magnetization as $H$ increases, there is less erasure, which results in an increased *net* magnetization in this layer. However, as $H$ increases, a point such as (a) is eventually increased to saturation. The region beyond (a) is of sufficiently small slope so that the effective gap width is now increased, producing increased attenuation.

If $H$ is increased sufficiently so that the outer oxide layers now suffer increased attenuation, the inner layers, subject to a smaller field, will not yet have passed their peak. Thus, there is a region of some field where the tape magnetization is of increased uniformity through the thickness. Hence, the field operating point which would minimize the effect of a dropout is somewhat beyond this maximum magnetization point. It is speculated that the effective gap width at which this maximum magnetization occurs should be of the order of half the maximum packing density distance (or $\lambda/2$ min for sine waves). Thus, for increased reliability, where distortion is of little importance, a general rule might be to keep the record (and reproduce) gap widths as large as possible, namely at $g_e \sim 1$. Further analytical and experimental work on this problem should be worthwhile.

## CONCLUSIONS

In essence, the recording of an unbiased continuous signal on a magnetic medium using a magnetic gap is a combined magnetic "scanning" and interference process. Analyzing particularly sine wave recording, we find that this combined process is, to a good approximation, a function of only one variable, namely $g_e=\lambda/2l'$, where $l'$ is the effective magnetic gap width. Applying the basic analysis to the actual head-tape system graphically, we find there is a functional dependence of $l'$ on a host of factors. In this manner, not only is physical insight gained into the basic magnetization processes, but also their interaction to produce particular phenomena is understood. Furthermore, semiquantitative results have been obtained showing the variation of attenuation, phase, and distortion with $g$, relative spacing, and wavelength. The phenomenon of a saturating field producing a maximum magnetization is qualitatively analyzed; lower limits to recorded wavelengths are estimated. It is pointed out that the effect of attenuation and phase shift at the shorter wavelengths is of particular relevance to the timing of signals and to FM systems.

The analysis is based on a series of approximations such as:

1) Simplified hysteresis curves.
2) Certain mathematical simplifications.
3) Graphical methods.
4) Simplified criteria for the lower wavelength limit.

Because of this, the numerical results are at most semiquantitative. The value of a more exact analysis is doubtful unless there is some very particular purpose in mind. The inclusion of the nonuniform characteristics of tape magnetization in the evaluation of the reproduced signal is straightforward, but tedious. However, it would probably give a closer correspondence between the theoretical and experimental reproduce curves at the shorter wavelengths.

Experiments have been run showing the distortion for $g_e>1$, the attenuation for $g_e<1$ and the effect of spacing. Generally, these experiments verified the analysis. It is suggested, however, that an extended series of experiments be run to test the analysis more thoroughly and determine whether or not it should be extended.

## NOTATION

$a = H_a/H_0$
$g = \lambda/2l$
$g_e$ = effective $g$
$g_0 = g/(1-ag)$
$H$ = gap magnetic field
$H_a$ = gap magnetic field at which $k$ becomes nonzero
$H_0$ = gap magnetic field amplitude
$H_s$ = gap magnetic saturation field
$k$ = tape susceptibility
$k_e$ = tape effective susceptibility
$l$ = gap width
$l'$ = effective gap width
$M$ = tape magnetization
$M_i$ = $i$th tape magnetization
$M_{m,n}$ = net tape magnetization after $m$ magnetizations in a series capable of $n$ magnetizations
$t$ = time
$x, s$ = distance from the gap centerline in length and signal phase units
$x_1$, $s_1$ = distance from the tape coordinate origin in length and signal phase units
$x_0$, $s_0$ = distance from the tape coordinate origin to the gap centerline in length and signal phase units
$y$ = spacing to the head
$\lambda$ = wavelength
$\eta = y/l$
$\theta = M = 0$ displacement from the nondistorted sine wave
$\phi$ = recorded phase shift
$f$ = input frequency

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# The Mechanism of AC-Biased Magnetic Recording*

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*Summary*—**The mechanism of ac-biased magnetic recording is directly related to the physical and magnetic properties of the recording medium. A theory has been developed which describes this relationship, both qualitatively and quantitatively. The action of ac bias on a single-domain particle is examined, and the factors determining its remanent state are analyzed. When the analysis is extended to an aggregate of such particles, it is found that the interaction fields created by the particles themselves are responsible for the biased recording mechanism. The transfer characteristic obtained with ac biasing is derived directly from the distribution of interaction fields in the aggregate material.**

TO achieve a more detailed knowledge of magnetic recording, it is necessary to determine accurately the relationship between the ac-biased transfer characteristic and the physical and magnetic properties of the tape which influence it. It is necessary to understand these relationships at least qualitatively before the performance characteristics can be improved by other than cut and try methods. A theory has been developed which describes this relationship both qualitatively and quantitatively.

In ac-biased magnetic recording a large high-frequency alternating signal is added to the signal to be recorded and both are impressed upon the record head simultaneously. Thus, as the tape passes in front of the record head it is subjected to a field consisting of the intense high-frequency bias and the information signal to be recorded. The resulting transfer characteristic is shown in Fig. 1. For comparison, the transfer characteristic which is obtained in the absence of the high-frequency ac bias is also shown. Thus, it may be seen that the application of the ac bias has a considerable effect on both the linearity and the sensitivity of the recording process. The resulting transfer characteristic is very linear up to about 35 per cent of saturation magnetization, and the sensitivity near the origin may be as much as several hundred times that which exists without bias.

AC-biased magnetic recording can best be understood by examining a similar but not identical phenomenon, anhysteretic magnetization. In anhysteretic magnetization, just as in ac-biased magnetic recording, a large alternating bias field and a smaller signal field are applied simultaneously to the sample to be magnetized. In anhysteretic magnetization, the bias field is large enough so that its alternate peaks saturate the material, and it is reduced very slowly to zero, while the dc or signal field is held constant. In ac-biased magnetic recording, of course, both the bias field and the signal field applied to an element of tape are reduced simultaneously

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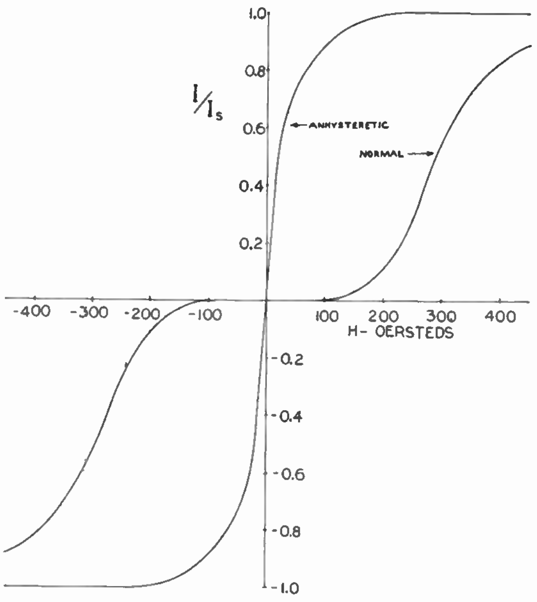

Fig. 1—Magnetization characteristics.

as that element moves away from the field of the recording head. The two types of magnetization are quite similar with a notable exception being that in the case of ac-biased recording very large initial values of the bias cause a reduction in sensitivity whereas in anhysteretic magnetization this does not occur. The mechanism by which each element of tape receives its final magnetization is identical in both cases. A new theory describing the anhysteretic magnetization process has recently been proposed by the author.[1] A discussion of this theory is also included here.

The mechanism of anhysteretic magnetization may be best explained by considering first the effect of the process on a single particle to which a dc magnetizing field $H_s$ and alternating randomizing field $H_b$ are applied. Consider the particle as being isolated from all others and as having a symmetrical rectangular $B$-$H$ loop (Fig. 2). If the ac field starts from a peak value larger than $H_s+H_c$ and decreases slowly, then if $H_s$ is positive, a point will be reached where the positive peaks of the bias field will exceed $H_c$ but the negative peaks will not. Therefore, the particle magnetization will remain at $+m_s$. Likewise, if $H_s$ is negative, the magnetization will be $-m_s$. These conditions will always occur so long as the alternating field decreases slowly enough so that the difference in value between consecutive peaks of alternate polarity, $\Delta H$, is less than $2H_s$. It follows that a large group of particles (neglecting interactions) will act in the same way; namely, all particles will remain at the magnetization of the same sense as the applied dc field $H_s$, so long as the alternating field started out larger than the $H_c+H_s$ of all particles. This

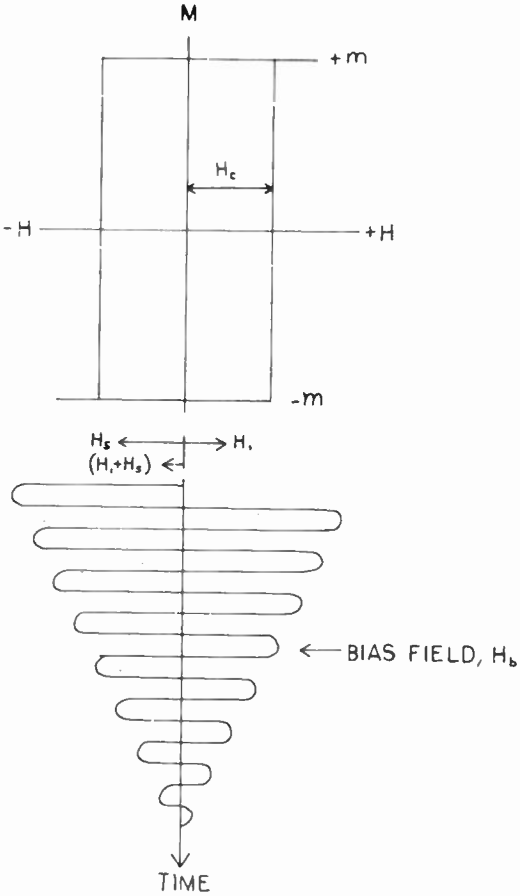

Fig. 2—$B$-$H$ loop of a single particle and fields acting upon it.

applies even for a distribution of coercive forces and for a distribution of particle direction, where the Stoner and Wohlfarth[2] model applies. The anhysteretic characteristic from any such group of particles therefore will rise with infinite slope from the origin, and all particles will be saturated for any applied dc field $H_s$. Westmijze[3] explains the finite slope at the origin by introducing a demagnetizing field. Since the presence of such a field is questionable, it is desirable to have an explanation not requiring the assumption of a demagnetizing field.

The finite slope of the anhysteretic magnetization characteristic from the origin may be explained by including the interaction fields. This has been done using the Preisach diagram by Daniel and Levine[4] and Woodward and Della-Torre.[5] Although this technique serves to describe the phenomenon in question, it is complicated and does not provide a separation of vari-

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ables, which the following technique does accomplish.

Consider now the previous particle, but with a small interaction field $H_i$ which is the sum of the fields from all the surrounding particles. Assume that the value (or at least the distribution of values) of $H_i$ is determined by the geometrical arrangement of the surrounding particles and is independent of the applied field and the magnetization of the assembly of particles. Now, $H_i$ will act in the same manner as did $H_s$ in the previous example; that is, for a given particle, if $H_i$ is positive, the particle will always remain at $+m_s$ after the application of an alternating bias field. With no signal field applied, and assuming a symmetrical distribution of $H_i$, one-half the particles will remain at $+m_s$ and the other half at $-m_s$. Now consider the additional application of a small external dc field $H_s$ to this particle. The net dc field will be $H_s+H_i$. The particle will acquire its "normal" zero-field remanence after the bias application *unless* $H_s$ causes this net field to reverse its zero-signal polarity. Thus, only when $H_s$ is opposite in polarity and larger than $H_i$ will the particle become magnetized in the sense opposite $H_i$ after the application of the alternating bias field. Thus, all the particles for which $H_i < -H_s$ will be magnetized in the same sense as $H_s$. The total magnetization of an aggregate of such particles will be proportional to the number of particles for which $H_i < -H_s$. If there is a distribution function describing the relative number of particles which experience a given interaction field, the total net magnetization may be determined for any value of $H_s$. The cumulative form of this distribution function will describe the $M$ vs $H_s$ characteristic.

Thus, the anhysteretic magnetization characteristic (and the ac-biased magnetic recording characteristic) is a function of and may be determined from the distribution of interaction fields. The foregoing analysis assumes the interaction fields to be fixed and independent of the magnetization. This, of course, is not really the case. In actuality, there is no fixed interaction field when the bias field is at its maximum because the magnetization at every point throughout the material is reversed every half cycle. As the bias field is reduced, however, and the magnetization of some particles becomes fixed, a fixed interaction field will start to build up. The average value of the fixed interaction field will, as may be seen from a derivation to follow, be proportional to the total number of particles which have achieved their final state. From this, it may be deduced that the average effective interaction field during the anhysteretic magnetization process will be just one-half the value which exists at the end of the process. Thus, the anhysteretic process can be described by assuming a fixed value of the interaction field equal to one-half the actual final value.

An expression may now be obtained for $H_i = f(H)$. Assuming an aggregate in which the particle-to-particle spacing is such that the field from each particle may be expressed as that from a dipole, and assuming an average magnetic moment $\bar{p}$, the magnitude of the field at some point $q$ from a particle with moment $\bar{p}$ at a distance $r$ is

$$|H_q| = \frac{\bar{p}}{r^3}\sqrt{3\cos^2\theta + 1},$$

where $\theta$ is the angle between $r$ and the particle axis.

The mean square field from $n$ particles at radius $r$ and oriented randomly is

$$|H_q|^2 = \frac{n}{4\pi}\frac{\bar{p}^2}{r^6}\int_0^{2\pi} d\phi \int_0^{\pi} (1 + 3\cos^2\theta)\sin\theta d\theta = 2n\frac{\bar{p}^2}{r^6}$$

where $\phi$ and $\theta$ are the angles designating the direction of $\bar{p}$.

Now if $dn$ is the number of particles in a thin spherical shell at radius $r$ and $D$ is the number of particles per unit volume,

$$dn = 4\pi r^2 D dr$$

and

$$|H_q|^2 = 2\frac{\bar{p}^2}{r^6}4\pi r^2 D dr = 8\pi\frac{\bar{p}^2}{r^4}D dr.$$

The mean square magnitude of the (interaction) field from all particles may now be obtained by integrating the above expression from the minimum particle spacing $r_0$ to $\infty$. Thus,

$$\sigma_{H_i}{}^2 = \int_{r_0}^{\infty} 8\pi D\bar{p}^2\frac{dr}{r^4} = 8\pi D\bar{p}^2\left| -\frac{1}{3r^3}\right|_{r_0}^{\infty} = 8\pi D\frac{\bar{p}^2}{r_0{}^3}\cdot$$

But

$$r_0{}^3 = \frac{1}{D} \text{ (approximately).}$$

Therefore,

$$\sigma_{H_i}{}^2 = \frac{8}{3}\pi D^2\bar{p}^2$$

and

$$\sigma_{H_i} = 2.9D\bar{p}.$$

Thus, an expression is obtained which states that the root mean square value of the interaction field is directly proportional to the particle density and the average particle moment. It may also be expressed in terms of other factors as follows. Now, $D = k/v$ where $k$ = volumetric packing factor and $v$ = particle volume and $\bar{p} = vI_0$ where $I_0$ is the average particle magnetization. Then $\sigma_{H_i} = 2.9kI_0 = 2.9I_s$, since $kI_0$ is the magnetization $I_s$ of the aggregate material. The mean square component of $\sigma_{H_i}$ in the direction of any applied field will be

$$\sigma_{H_i}(x) = \frac{\sigma_{H_i}}{\sqrt{3}} = 1.7I_s.$$

This result is similar to that which Neél[6] calculated for the case of an ordered array.

Since the distribution of values of $H_i$ is random, it will have the form

$$p(H) = \frac{1}{\sqrt{2\pi}\,\sigma_{H_i}} e^{-H^2/2\sigma^2},$$

which is illustrated in Fig. 3(a). The integral of this function [Fig. 3(b)] will describe the anhysteretic transfer characteristic. It may be observed that this integral function is very similar in appearance to the biased-magnetic recording characteristic, an example of which is shown in the same figure. It is interesting to note that in reality the transfer characteristic of biased magnetic recording is nonlinear over most of its extent and only approximates a linear function near the origin because the deviation from linearity is so slight as to be unnoticeable and immeasurable. Some past attempts at analyzing the biased recording transfer characteristic have sought a function which was inherently linear whereas the theory described here shows that this is not the case and describes the transfer characteristic over its entire extent.

The slope of the characteristic at the origin will be $\chi$, the anhysteretic susceptibility. The value of $\chi$ may be obtained by setting $H=0$ in the preceding expression and substituting $0.5\,\sigma_{H_i}$ as the effective interaction field acting during the process and multiplying by the factor $I_s/0.5$ to obtain the result in terms of $I_s$ rather than the normalized function. Thus,

$$\chi = \frac{1.6}{\sigma_{H_i}} I_s.$$

But, as derived previously,

$$\sigma_{H_i} = 1.7 I_s$$

and

$$\chi = \frac{1.6 I_s}{1.7 I_s} = 0.94.$$

This, rather surprisingly, states that the anhysteretic susceptibility is a constant and therefore is independent of the saturation magnetization or the value of the interaction field. Variations from this value would only occur if $I_s$ and $\sigma_{H_i}$ varied independently of each other. This could occur if the particles were not distributed randomly, such as would be the case if they were severely clumped or if some ordering process such as orienting were to occur. Experimentally determined values of $\chi$ for supposedly unoriented tape samples ranged from 0.94 to 1.68. Values of $\chi$ for commercial recording tapes measured by Daniel and Levine[4] ranged from 1.43 to 3.58. It can be seen that there is fairly close agreement between experimental results and the theory proposed here for the cases where the particles are randomly distributed. And, as would be expected from theory, the characteristic is steeper at the origin for the case of oriented materials indicating a smaller value of interaction field.

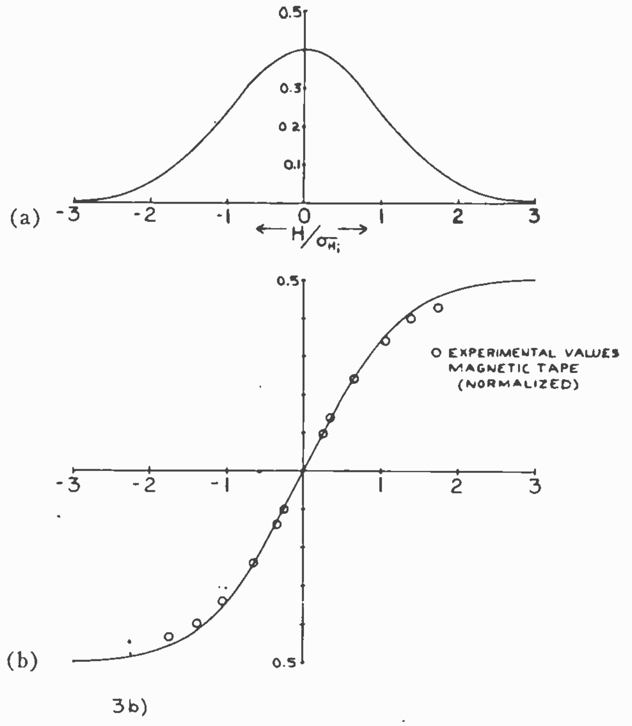

Fig. 3—(a) Distribution function. (b) Cumulative distribution.

In conclusion, the transfer characteristic obtained with ac-biased magnetic recording has been described in terms of the anhysteretic magnetization characteristic. It has been shown that the anhysteretic magnetization characteristic is determined by the distribution of interaction fields within the substance being magnetized. An expression has been derived to describe the interaction field distribution in terms of the physical and magnetic properties of the material. The integral of this distribution which should describe the anhysteretic magnetization characteristic is an extremely close approximation to the experimental case. Thus, biased magnetic recording is seen to be a fundamentally nonlinear process which appears to be linear only because the deviations from linearity are very small around the origin, which is the region used in most ac-biased magnetic recording. The theoretical value of the initial anhysteretic susceptibility is seen to be rather close to that obtained experimentally for the case of randomly distributed particles. As expected, deviations from this value occur for the case of oriented tapes.

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# Flutter in Magnetic Recording of Data*

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*Summary*—**Among the sources of error in magnetic tape recording, one of the more important is the distortion of the reproduced time scale generally described by the term "flutter." Flutter is defined as the deviation in reproduced frequency from the original recorded frequency, which results from nonuniform speed of the recording medium during recording and reproduction.**

**The present paper provides a qualitative and quantitative discussion of flutter including:**

1) **Causes—eccentricities, resonances, frictional variations.**
2) **Effects—FM noise, AM noise, time displacement error.**
3) **Measurements—methods, units and relations between them.**
4) **Compensation—methods and limitations.**

**The object of the paper is to collect the essential characteristics of flutter in a way that will be of value to users of magnetic tape recording equipment.**

## INTRODUCTION

WHILE magnetic tape recording of data is woefully lacking in standards for measurement, definition, and description, most people seem to agree that "flutter" can be defined as "the deviation in the reproduced frequency from the originally recorded frequency which is a result of nonuniform speed of the recording medium during recording or reproduction."[1,2]

This might be considered to include very slow variations such as might be caused by the changes which occur in power line frequency in the course of a day, but there is an undefined lower limit usually established by the fact that the measurement is limited to a few seconds. These slower variations are segregated and called average speed variation or "drift." It should be noted, however, that when recordings are made at very slow tape speeds and then reproduced fast, these variations could come into a range that would be observed or, more important, would be within the range of the recorded information.

Data can be recorded by digital or analog techniques. Digital recording uses codes which represent sampled readings made at equally spaced intervals. When these are reproduced, each reading can be delayed and read out at newly generated equal time intervals. Flutter is then only a problem in that it influences the design of the readout circuits and the density of recording that can be used. This is quite different from analog recording where it is assumed that tape velocity is perfectly constant and where the reproduced time scale depends entirely on the mechanical drive system which imparts motion to the tape as it passes the heads.

Thus, analog methods are much more sensitive to flutter; the type of transports used for them will be considered. Since digital data pulses are recorded at discrete intervals, these systems are not so much concerned with flutter as with the variations in these intervals. This is called "time displacement error" and is the integral of the flutter over that interval.

## CAUSES OF FLUTTER

All flutter has its beginning in an eccentricity, irregularity or rough surface somewhere. In the results, however, the degree to which these sources are coupled to the section of tape at the heads is equally important. One writer has said that there are three approaches to designing a low flutter transport,[3] as follows:

1) eliminate the sources;
2) isolate the sources; and
3) regulate out the resultant variations.

In the struggle for minimum flutter, present-day analog tape transports use all three approaches[4,5] and do achieve remarkably low values when all of the possibilities are considered.

Table I lists most of the possible sources of flutter. Of these, the variations in motor torques, bearing torque, and eccentricities of rotating elements could produce cyclic variations in flutter. The others would

TABLE I

1) Eccentricities of capstan, pulleys, pressure rollers, rotating guides, reels and bearings.
2) Irregularities in the surface of tape and belts, and consequent frictional variations.
3) Irregularities in width of tape, or belts causing changes when or if the edges bear on a guide.
4) Nonuniform compliance in belts or tape.
5) Nonuniform hardness in rubber pressure rollers.
6) Variations in bearing torque.
7) Cohesion between successive tape layers.
8) Variations in drive motor torque.
9) Variations in reel motor torque.

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tend to be more random. A typical analog tape transport is shown in Fig. 1. This uses the "closed-loop" principle in which the section of tape passing over the heads is clamped to the two opposite sides of the capstan and thereby largely isolated from the tape passing to and from the reels. This greatly reduces the effects of any disturbances arising in the reels or reel motors on the tape motion. The capstan represents a dividing line in the flutter frequency spectrum. With its large flywheel, it cannot change speed fast, and, therefore low-frequency flutter would be expected to arise in its drive, while flutter above 10 or 20 cps would be expected to enter in the section of tape between the pressure rollers. An electrical analog is helpful in analysis, and an approximate one for the drive system of Fig. 1 is shown as Fig. 2. Sources of disturbances are shown as current entering at appropriate points with tage to identify them according to their order in Table I.

The common eccentricities, such as capstan run-out, are not included in this because they are generally so small in high-quality transports that their contribution to the total is negligible. If they should be found, they can be quite easily identified.

To the left of the dividing line where the capstan converts its rotary motion to linear tape motion is a mechanical system with compliances and inertias which generally have quite low resonant frequencies. When excited by the random forces from the belt and bearing

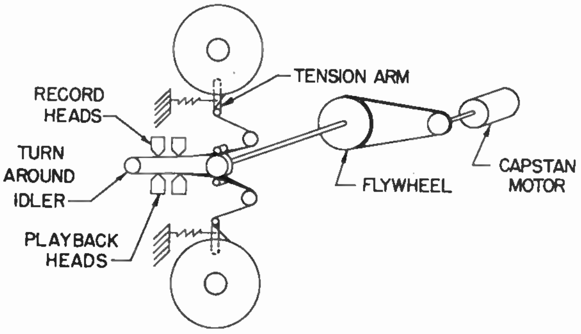
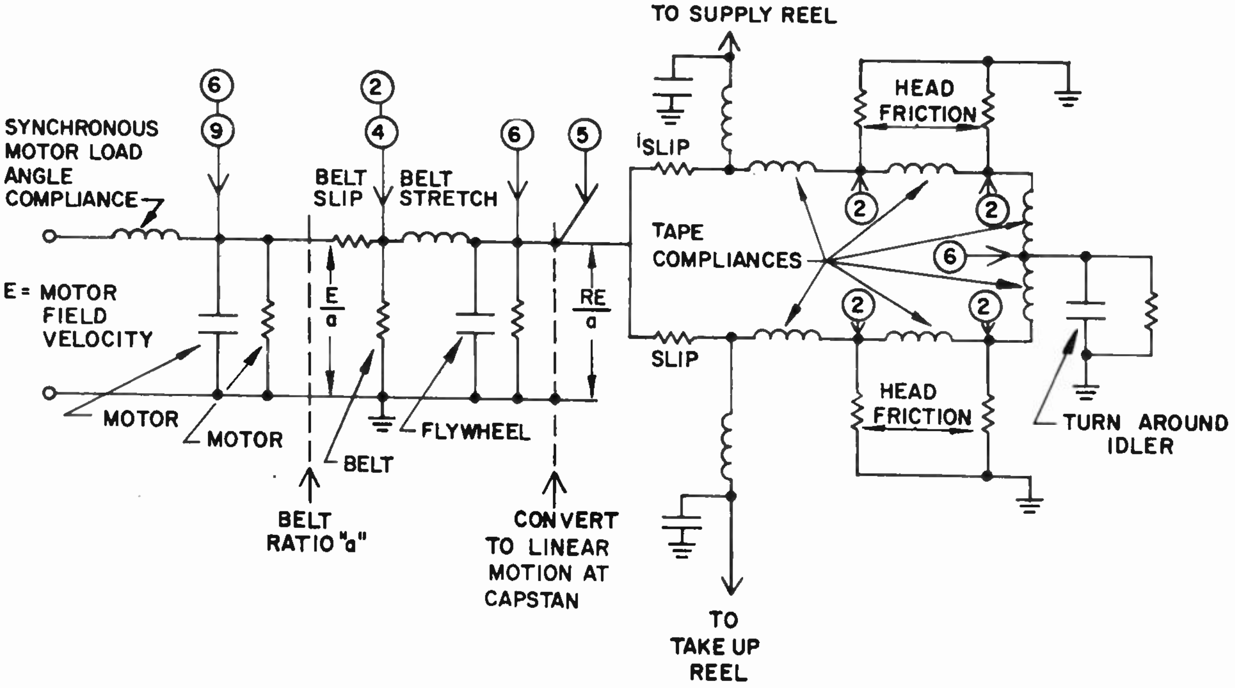


Fig. 1—Principal parts of typical "closed loop" tape drive.



$E$ = velocity
$I$ = force or torque
$C$ = inertia
$L$ = compliance
Circled numbers indicate possible disturbing force as listed in Table I.

Fig. 2—Electrical analog of drive system in Fig. 1.

friction, these resonances may show up as the principal low-frequency flutter components. Disturbances at frequencies above the highest resonance of this system will be attenuated. To the right of the capstan, the analog could be made more complex to represent the distributed tape mass and provide for the various modes of vibration of the stretched tape.[6] As it stands, it would be correct for the commonly observed oscillation involving the inertia of the turn-around idler and tape compliance. The tape can vibrate in both longitudinal and transverse modes but many of them seem to fall at frequencies higher than the 10-kc limit of most flutter measurements. Above 100 cps or so the flutter spectrum becomes quite uniform with these randomly distributed components attributed to the variations in friction as the rough tape surface passes over the heads.

It might be assumed that each bump or irregularity in friction subtracts an increment of energy from the moving system which is independent of tape speed. Then the total flutter within a band proportional to the tape speed should vary inversely with the square root of tape speed. However, the published data of several manufacturers shows more nearly an inverse cube root relation for the increase in flutter at the lower tape speeds.

## DESCRIPTION OF FLUTTER

From the foregoing, it is not surprising to find that the motion of the tape past the heads is subjected to a complex combination of variations consisting of a few frequency bands within which flutter may be relatively high, plus a more or less uniform distribution over all of the frequency range being observed.

Fig. 3 is an illustration showing reasonably typical frequency analyses made at a high and a low tape speed. These are fictitious curves and any resemblance to characteristics of transports living or dead is purely coincidental. These are plots of what might be termed a "flutter density" as a function of frequency which is a useful means for estimating the contribution of various components to the total. This "flutter density" would be defined as the rms flutter observed with a filter having a rectangular pass-band one cycle wide. This corresponds closely to the power spectrum commonly used to describe the frequency analysis of randomly varying phenomena, and flutter seems to fit this description as well as any other.

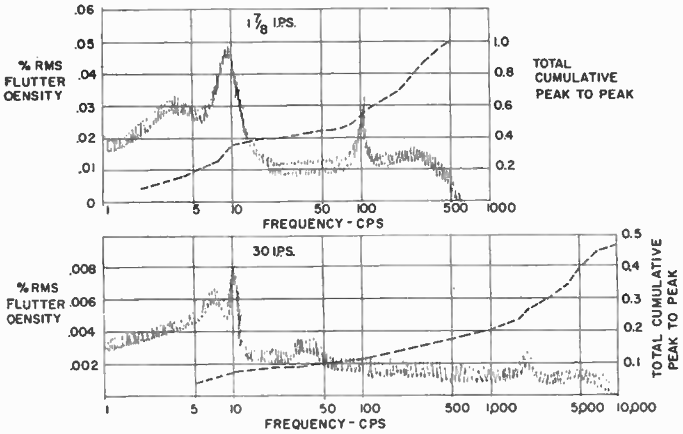


Fig. 3—Flutter spectra representative of what the drives of Figs. 1 and 2 might produce. The dashed line is the cumulative flutter that results from these spectra.

In order to compute the total flutter from the flutter density spectrum, it can be sectionalized into frequency bands within which the flutter density is relatively constant. Then

$$F_{\text{total}} = \sqrt{\sum_{f_{\min}}^{f_{\max}} F_{d_1}{}^2 BW_1 + F_{d_2}{}^2 BW_2 + \text{etc.}} \qquad (1)$$

This value $F_{\text{total}}$ is the rms value for the total flutter, and the peak, or peak-to-peak value would be related by the normal distribution for a random function. This says that 5 per cent of the time the amplitude will exceed 2.0 times the rms value, and 1 per cent of the time it will exceed 2.5 times the rms value. Thus, depending on the observer and the length of the observation, the familiar peak-to-peak flutter figure will be from 4 to 5 times the rms value.

In working with flutter, it is common to show a cumulative curve which can be obtained from the flutter density spectrum by adding the contribution of components to successively higher frequencies. The cumulative curves for the two fictitious examples are superimposed on the spectra in Fig. 3 to illustrate this and to emphasize the relative contributions of the various parts. In this, a factor of 4.2 was taken to relate the peak-to-peak to rms flutter.

## FLUTTER MEASUREMENT

The foregoing approach to the description of flutter has been taken to make it possible to show readily the relation between the various ways in which flutter has been described. The "IRE Standards on Sound Recording and Reproducing: Methods for Flutter Measurement in Sound Recoreing, 1953"[1] uses an rms figure in which the frequency band is limited to the range from 0.5 to 200 cps. An extension is the "flutter index" in which lower-frequency components are weighted more strongly to give a figure representing average human sensitivity to flutter in recorded sound. Currently, there are no standards for flutter measurement or definitions in instrumentation applications, although there is an IRE subcommittee working on one,[2] and the most recent IRIG telemetry recording standard[7] includes suggested methods.

Sometimes rms flutter figures are used in specifica-

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[6] General Kinetics, Inc., Arlington, Va., 2nd Quart. Rept., Contract No. DA18-119-sc-42; 1958.

[7] "Standards for testing speed errors in instrumentation type magnetic tape recorders," pt. 7 of IRIG Document No. 106-60, "Telemetry Standards," November, 1960.

tions, but peak-to-peak values are most common. Obviously, whether an rms or peak-to-peak reading is given, it is not a complete description without knowledge of the bandwidth within which the measurement was made, and the most complete description is a spectrum showing flutter density as a function of frequency.

When a signal is recorded and reproduced, the flux in the playback head is frequency modulated by the flutter during recording and during playback. Most heads produce output proportional to the rate of change of this flux so that the output is also amplitude modulated by the flutter. Simplified (2) and (3) below give the flux and playback voltage, respectively, for a simple sinusoidal signal recorded and reproduced on transports each having single sinusoidal flutter components with different frequencies and amplitudes.

$$\phi_H = A \sin p\omega_1\left(T + \frac{a}{p\omega_2}\cos p\omega_2 T - \frac{b}{\omega_3}\cos \omega_3 T\right). \quad (2)$$

$$E_H = K\frac{d\phi H}{dT} = AKp\omega_1 \cdot [1 - a\sin p\omega_2 T + b \sin \omega_3 T] \cdot \cos p\omega_1\left(T + \frac{a}{p\omega_2}\cos p\omega_2 T - \frac{b}{\omega_3}\cos \omega_3 T\right). \quad (3)$$

Recorded signal $= A \sin \omega_1 T$

$$V_{\text{record}} = V_0(1 + a \sin \omega_2 T)$$

$$V_{\text{playback}} = V_1(1 + b \sin \omega_3 T)$$

$$P = \frac{V_1}{V_0}.$$

In (3), the terms in the bracket represent the amplitude modulation. Coefficients $a$ and $b$ are the peak fractional flutter values. In analog transports, they would generally not exceed 1 per cent so that the amplitude modulation can be neglected since it would be smaller than the amplitude variations usually expected from tape variations.

The argument of the cosine term in (3) represents the frequency modulations occurring in record and playback. In this simplified equation, a recording made and played back on the same transport at the same speed could have a condition where $a=b$ and $w_2=w_3$, so that the flutter would cancel. Something like this is sometimes approached in practice, but there is generally enough difference in velocity to result in a slow beat as the phase between the two principal flutter frequencies shifts. With single sinusoidal flutter components, this frequency modulation could change from zero to $a+b$, but again, in a practical case, there are many components whose amplitudes and phases are random so that the chance of this is not great. Perhaps the best chance to have this effect would be where flutter was checked while recording and playing back simultaneously. Then flutter components at frequencies such that

$$\text{separation between heads} = \frac{N\text{ (tape speed)}}{\text{flutter frequency}}$$

would effectively be cancelled because record and playback speeds would be equal while the effects of flutter at twice these frequencies would be doubled because there would then be a maximum difference between record and playback speeds.

The fact that flutter can only be sensed in the playback operation makes it difficult to separate that which arises in record from that present in playback. The ideal would be to have a perfectly recorded tape in which there was absolutely no variation in the recorded wavelengths. This is not possible, but as has been noted, flutter is generally less at high tape speeds than at low ones; therefore an approximation to a perfect recording can be made by recording at one of the higher available tape speeds. Then, when this is played back at lower speeds, most of the flutter found can be attributed to the playback process. This is a useful technique in finding causes of flutter and is a valid measure of the quality of a transport so long as it is recognized that recording and playing back at the same low speed would result in an increase in apparent flutter. As a measure of transport quality, there is a practical advantage in that tests can be run more quickly from a single recording, made at a high tape speed, than when a new recording is made at each speed.

Flutter is almost universally measured by first recording a stable frequency and then playing it back through limiting amplifiers to a frequency detector or discriminator.[8,9] The frequency is chosen to be such that the recorded wavelength is about 1 mil. This is low enough to produce reasonably steady playback amplitude and high enough to measure flutter frequency components which would fall within the data band recorded in FM recording systems. Since there are possibilities of effective "cancellation" and because transport conditions vary from one end of a reel to the other, it is best to take several readings at several places going from full to empty supply reel.

The discriminator must be very stable, linear and noise-free. It should show little change in output for quite large variations of input amplitude, and the level from the playback head must be such that the limiting amplifiers operate correctly. Thus, a discriminator intended for flutter measurement should be considerably more sensitive and noise-free than one for data. Discriminators designed for demodulating telemetry sub-

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[8] J. T. Mullin, "Measurement of flutter and wow in magnetic tape instrumentation recorders," *J. Audio Eng. Soc.*, vol. 3, p. 151; July, 1955.

[9] C. B. Stanley, "An approach to qualitative methods for evaluation of magnetic recording system performance," 1957 IRE NATIONAL CONVENTION RECORD, pt. 7, pp. 82–94.

carriers are frequently used because they are designed to give full-scale output with a peak deviation of only 7.5 per cent. But a peak flutter of 0.5 per cent would be only 7 per cent of their normal full scale.

The output from the discriminator is a voltage whose instantaneous value represents the instantaneous speed of the tape as a function of time. The problem now is what to do with it. As pointed out earlier, the most complete representation would be a flutter spectrum, but for some purposes it is desirable to have a single number to use as a figure-of-merit.

A cumulative peak-to-peak figure for flutter within a stated bandwidth has come to be widely used for this purpose. There are some good reasons for this:

1) The oscilloscope is the only generally available laboratory instrument whose frequency range extends from dc to higher than any flutter measured yet.
2) In an FM recording system, it represents the maximum range of errors due to flutter.
3) When the output is displayed on an oscilloscope, it represents the width of the trace.
4) It is the biggest percentage figure that can be assigned. Historically this reflects the disappointments that came from trying to evaluate a data recorder from the rms flutter rating of sound recorders which only included frequencies from 2 to 200 or 300 cps.

The difficulty is that measurement must be made on an oscillograph and evaluated by watching the trace. Assuming that the flutter amplitudes follow something like a Gaussian distribution, the highest peak amplitudes are relatively infrequent and, of course, not evenly distributed in time. Theoretically, at least, there is no absolute peak value; if the observations were carried on long enough any amplitude could be seen. In addition, there are amplitude effects. The tape playback voltage is not constant and when it falls far enough, a dropout occurs which produces a very large output at the discriminator. Amplitude changes smaller than dropout size can make an output pulse large compared to the very small percentage deviation that constitutes flutter in a reasonably good analog transport. This has been recognized by specifications such as "peak-to-peak flutter not to exceed '*X*' per cent for '*Y*' per cent of the time." This is a move in the right direction but it does make it hard on the tester. An accurate reading of this type can be made by photographing a cathode ray scope or by a direct recording oscillograph. Then one must go over the trace summing the time intervals during which the specified level was exceeded. This is not a quick measurement. Complicated devices which would essentially compute amplitude distribution could be devised but there does seem to be a need for a relatively simple circuit or device which could be universally accepted as standard to give a reliable, repeatable meter indication of a figure of merit for flutter. If it could be established that flutter had a truly Gaussian distribution, the relations between peak values, rms, and average would also be established. Then, any of these measurements would be equally valid and useful if used with due regard to these relations and to the frequency limits of the measuring equipment.

## FLUTTER EFFECTS

When a frequency modulated carrier is used to record data, the output variations which show the flutter for measurement purposes are present and constitute the major part of the system noise. Its spectrum would correspond to that of the flutter, and, therefore the discussion of flutter applies equally to the noise in an FM recording system. The noise level in terms of the full-scale output depends on the full-scale deviation of the carrier, and the relative noise level improves as the deviation increases.

$$S/N = \frac{\text{per cent deviation}}{\text{per cent flutter}}.$$

When data recorded on tape are used with a wave analyzer the relatively narrow band of the analyzer greatly reduces the noise within the band, and the useful dynamic range is therefore much greater than the signal-to-noise ratio as usually specified for the maximum bandwidth would indicate. For example, assuming a white noise or uniform distribution of flutter over the pass band, an analyzer having a 100-cps pass band would only find 1/10 the noise as specified for a 10-kc band, which is a 20-db improvement in signal-to-noise ratio within this band.

Flutter also frequency modulates the recorded data, which means that a single recorded sine wave would be spread out over a frequency band in which sidebands related to the flutter frequencies would be distributed. In the simplest case where there is a single sinusoidal flutter frequency, there would also be a single set of sidebands according to the well-known representation of a frequency modulated carrier.[10] This means that if the analyzer is to measure the amplitude of components within a band correctly, it must have an increase in bandwidth sufficient to include all of the sidebands produced by the flutter modulation. Most of the energy in the sidebands of a frequency modulated carrier is within the band equal to twice the deviation or

$$B\omega_{\min} = 2af_d,$$

$$a = \text{fractional peak flutter},$$

$$f_d = \text{recorded data frequency}.$$

Thus the bandwidth required increases with increasing data frequency, and flutter must be very small for analysis with high resolution at high frequencies. For ex-

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[10] J. G. Frayne and H. Wolfe, "Elements of Sound Recording," John Wiley and Sons, Inc., New York, N. Y.; 1950.

ample, even 0.05 per cent peak flutter at 10,000 cps would limit the resolution to about 5 cps to avoid significant amplitude error.

## TIME DISPLACEMENT ERROR

Related to flutter is time displacement error. This is another term which needs a solid definition, and what is meant here is the error in the time between two events recorded on a single track when played back from a tape recording. The real difference from flutter is that the time intervals are usually greater than the period of the carriers used for flutter measurement, which tends to reduce the effects of higher frequency components.

In Fig. 4 it is shown how the separation between events recorded on the tape being the integral of the tape speed over the interval between those events would have a generally decreasing percentage error as the interval increases. The percentage error is also seen to decrease with increasing flutter frequency.

If the flutter in a tape transport is considered to be at single sinusoidal frequencies during record and playback, the reproduced period $T'$ for a recorded period $T$ is found to be

$$T' = \frac{T}{P}\left[1 + a\cos\theta_1 \frac{\sin X}{X} - b\cos\theta_2 \frac{\sin Y}{Y}\right] \tag{4}$$

where

$$V_{\text{record}} = V_0[1 + a\cos(\omega_2 t + \theta_1)]$$

$$X = \frac{\omega_2 T}{2}, \qquad Y = \frac{\omega_3 T}{2P}, \qquad P = \frac{V_1}{V_0}$$

$$V_{\text{playback}} = V_1[1 + b\cos\omega_3 t + \theta_2)]$$

and

$$\frac{T' - T}{T}(\text{max}) = a\frac{\sin X}{X} + b\frac{\sin Y}{Y}\cdot \tag{5}$$

Thus in transports with small flutter this time displacement error will be small, particularly where the interval is large. For example, consider a standard PDM pulse with a period of 700 μsec. When the flutter frequency reaches 720 cps, (sin $X/X$) in (5) reaches its first zero so that frequencies much above this are losing influence. Cumulative peak-to-peak flutter for a transport at 30 or 60 inches per second at frequencies below 2000 cps would be less than 0.3 per cent or a peak of 0.15. Thus the maximum timing error should not exceed one- or two-tenths of a per cent which would be 1.4 μsec. At the other end of the range where the period is 90 μsec, the contributions of higher flutter frequencies would result in a larger percentage error, but would still be under one μsec or one per cent of this shorter time.

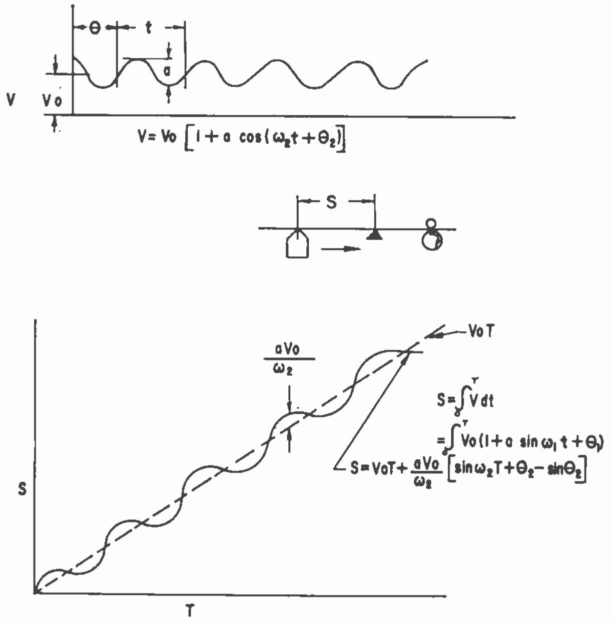

Fig. 4—Variations in velocity and distance to head of a point on the tape when the drive has a single sinusoidal flutter component.

There is no generally accepted method for measuring time displacement error. Several have been reported.[11–15] One is to record square pulses and derive short pulses from their reproduced sides. These then intensity modulate an oscilloscope being swept linearly. The resulting spots on the face of the oscilloscope are photographed on continuously moving film together with pulses at 1/10 the sweep period to provide a reference grid. Another method[12] is to produce peak amplitudes in sawtooth waves which are proportional to their time separations, by causing successive reproduced pulses to discharge a capacitor which is being charged at a constant rate. Using either of these methods, it would probably be difficult to measure the small timing differences found in transports having low flutter. When the pulses are widely separated, the error would be reduced by averaging, and when they are closely spaced, the playback rise times are slow so that it would be difficult to separate amplitude and time variations. Time displacement error is of most importance in digital recording where the fast start-stop transports have more flutter so that it becomes significant.[14]

## COMPENSATION

When the best transport design cannot sufficiently reduce flutter or when considerations of size, weight, en-

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[11] J. F. Sweeney, "A method for measuring the changes introduced in recorded time intervals by a recorder-reproducer," IRE TRANS. ON AUDIO, no. PGA-7, pp. 24–29; May, 1952.

[12] E. N. Dingley, Jr., "Measuring the stability of sonic recorders," IRE TRANS. ON AUDIO, no. PGA-7, pp. 20–23; May, 1952.

[13] R. A. Skov, "Pulse time displacement in high density magnetic tape," *IBM J. Res. & Dev.*, vol. 2, pp. 130–141; April, 1958.

[14] P. A. Harding, "Measurement and elimination of flutter associated with periodic pulses," IRE TRANS. ON INSTRUMENTATION, vol. I-9, pp. 342–349; December, 1960.

[15] R. H. Prager, "Time errors in magnetic tape recording," *J. Audio Engrg. Soc.*, vol. 7, p. 81; April, 1959.

vironment or cost do not permit using the most elaborate tape drive, it is possible to improve the results by correcting the effects of flutter in the reproduced signals.[16]

This may be done either mechanically to try to produce variations in the playback tape speed equivalent to those which occurred during recording, or electrically by introducing signals to modify the output. Sometimes both techniques may find application. Mechanical compensation corrects the amplitude and frequency errors in the reproduced signal.

It is fairly common practice to correct for slow variations or drifts which may be caused by power line frequency variations and by changes in the length of the tape due to differences in temperature or humidity by a "tape speed servo" system. In this, a precise control tone, generally 60 cps, is recorded as an amplitude modulated carrier. During playback the tape speed is servo-controlled to make the control tone equal to another precise 60 cps source. This type of servo is limited to removing tape speed variations which occur no more rapidly than 1 or 2 cps.

Similar speed control servo systems have been devised which use higher frequency control tones and can correct faster variations but still limited to a few tens of cps. This would include most of the flutter thought of as being associated with the drive to the capstan.

To correct higher-frequency flutter components by electromechanical means would be difficult in the capstan drive. One suggestion has been to move the head by rotating it slightly on a mounting bearing.

With one or two exceptions, electrical compensation methods have been in conjunction with FM recording methods, and are usually limited to correcting the noise or amplitude effects in the reproduced data.

A true PDM system, however, would be partially self-compensating. If data were recorded so that a record pulse width were directly proportional to the input and the recording pulse-repetition rate were fixed, an output could be obtained from the average level of exactly reproduced pulses. Tape speed changes will not influence this average if the relative durations of pulse and period remain fixed. Compensation would thus be best where pulse and period were nearly equal but would be less exact at the end of their range where they differed most.

One method of compensation has been described[17] in which time as well as amplitude effects have been corrected in the reproduced data, but does not seem to have been widely used. Time displacement error between pulses has also been corrected by means of an electrically controlled delay.[13]

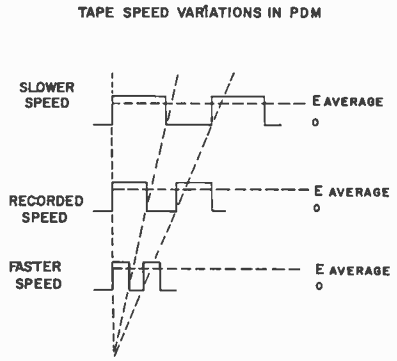

Fig. 5—Stability of the average output when reproducing PDM pulses at different tape speeds.

In compensating FM recordings, a precise fixed-reference control tone is recorded, and this is played back through a discriminator to produce an output proportional to the net record-reproduce flutter.[18,19]

This output then may most simply be subtracted from the output of a data discriminator to remove some of the amplitude effects. It does this perfectly only when the carrier is undeviated, but the output for deviated flutter still has some flutter noise left although less than there would have been without compensation. Consider the peak flutter output in 3 cases.

$$\begin{array}{ccc}
\text{Maximum positive deviation:} & \text{Zero deviation:} & \text{Maximum negative deviation:} \\
a(f_c+f_d) & af_c & a(f_c-f_d) \\
\underline{-af_c} & \underline{-af_c} & \underline{-af_c} \\
+af_d & 0 & -ad_d
\end{array}$$

Gain-change compensation:

$$\frac{a(f_c+f_d)}{a} \qquad \frac{af_c}{a} \qquad \frac{a(f_c-f_d)}{a}.$$

If, instead, the output of the "compensation discriminator" were used to control the gain of the data discriminator, the flutter effects would be corrected at all amplitudes. Since $f_c$ is a known constant, the output $af_c$ is a measure of $a$. Hence, all of the conditions cited could be multiplied by a factor $1/Kaf_c$, where $K=1/f_c$, so that $a$ would be removed in all cases.

To correct perfectly either with subtraction or gain-changing, there must be exact correspondence in time and amplitude between the correcting signal from the compensation discriminator and the flutter noise in the output of the data discriminator.

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[16] G. L. Davies, "Magnetic recorders for data recording under adverse environments," IRE TRANS. ON AUDIO, vol. AU-2, pp. 133–137; September–October, 1954.

[17] J. T. Mullin, "Flutter compensation for FM/FM telemetering recorder," 1953 IRE NATIONAL CONVENTION RECORD, pt. 1, pp. 57–65.

[18] R. L. Peshel, "The application of wow and flutter compensation techniques to FM magnetic recording systems," 1957 IRE NATIONAL CONVENTION RECORD, pt. 7, pp. 95–110.

[19] R. L. Peshel, "Wow and flutter compensation," *Instr. and Control Systems*, vol. 33, pp. 431; March, 1960.

Several factors are present which make this difficult:

1) Phase differences in the two discriminators or their output filters.
2) Phase or delay differences between band separation filters which may be used when more than one carrier is recorded on a single track as with FM/FM subcarriers.
3) Intertrack timing errors due to differential flutter or skew, which would be present when the data and compensation tones were recorded on different tape tracks as in the case with "wide-band" FM recording.

The circuit phase errors and delays are relatively fixed and can be adjusted, but the time differences between tracks is a variable and can only be improved by reducing tape skew. Phase errors are less serious at low frequencies, and compensation is therefore most effective in the lower part of the frequency band being reproduced, but is generally found valuable to about 7/10 of the maximum bandwidth in wideband FM systems. In systems where the compensation tone and data carriers are recorded on the same track the skew problem does not exist and very good improvement is obtained over the whole band.

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# Design of a Multichannel Magnetic Recording System for Frequency Multiplication*

S. HIMMELSTEIN†, MEMBER, IRE

*Summary*—**This paper concerns a multichannel magnetic tape recorder/reproducer whose primary function is to provide stable, real-time multiplication (100 times) of all frequencies present at the input. This is accomplished by the use of rotating playback head assembly, located near and "downstream" of a conventional record station. This arrangement yields a short processing delay and, because of the iterative scans, makes possible time division multiplexing of other system components. System requirements and characteristics are presented along with a discussion of the major engineering problems that had to be solved.**

## INTRODUCTION

THE magnetic tape record/playback frequency multiplier that is described in this paper was designed for use as an essential part of a unique sonar signal analysis system. The purpose of this system is to make possible the detection of coherent target echoes which are completely masked by background noise. A complete or even cursory treatment of this analysis technique is beyond the scope of this paper. Nonetheless, it is essential to know something of the intended application in order to appreciate the significance of system-imposed requirements. In this connection, the following should be noted:

1) Echo returns are the primary data to be recorded.
2) The frequency spectrum of these returns carries the essence of information.
3) All channels are to be evaluated by examining the entire spectrum in contiguous narrow bands.
4) Nonlinear distortion can, by the generation of spurious frequencies, cause erroneous system decisions.
5) An electronic wow and flutter compensation technique similar to that used in FM instrumentation recording systems can be used.

## SYSTEM REQUIREMENTS

In order to make the analysis scheme possible, the frequency multiplier must have the following general characteristics:

1) Wow and flutter—0.1 per cent peak, with compensation.
2) Frequency multiplication ratio—100 ± 0.2 per cent absolute with ± 0.05 per cent stability.
3) Frequency response—within ± 1 db from 50 to 250 cps referred to input; from 5000 to 25/000 cps referred to output.
4) Linearity—1 per cent over-all.
5) Signal-to-noise ratio—at least 35 db.

In addition, certain equipment characteristics were made obligatory by the end use and the attendant necessity for compatibility with other major system components. The more important ones are:

1) Multiplication must be done on a continuous basis with at most a few seconds delay between input and output.
2) The uninterrupted processing period must be at least ten hours.

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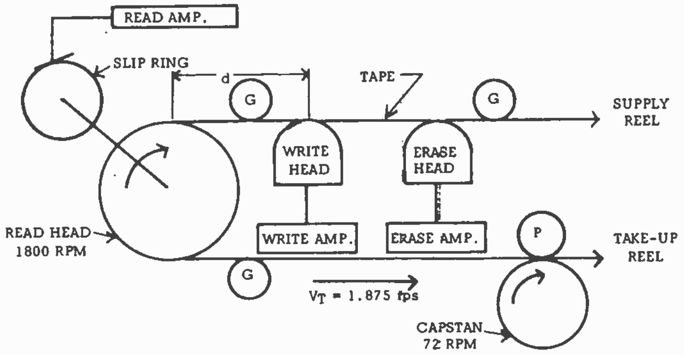
* Received by the PGA, July 6, 1961.

† S. Himmelstein and Co., Consulting Engineers, Chicago, Ill. The work described in this paper was done while the author was with Cook Electric Co., Morton Grove, Ill.



Multiplication ratio $= (V_P - V_T)/V_T = 100$
Processing delay $= d/V_T = 2$ sec
$V_T$ = Record tape speed = 1.875 ips
$V_p$ = Peripheral $P/B$ head speed = 189.375 ips
$d$ = Distance from write to read station
$G$ = Indicates tape guide
$P$ = Indicates pinch roller

Fig. 1—Simplified system block diagram, magnetic tape frequency multiplier.

3) Bi-directional operation with automatic reversal at end of reel must be provided and result in a maximum processing interruption of thirty seconds.
4) Thirteen-information channels plus one reference channel are required.
5) Inclusion of variety of safety interlocks, which will automatically shut down equipment and signal malfunctions to human operators in event of tension failures, tape breakage, circuit failures, etc.
6) Equipment must operate successfully from a 3-phase, 4-wire, 208-volt ± 10 per cent, 60-cps ± 5 per cent power supply.
7) The entire equipment must be housed in a sealed cabinet with cooling water but no external cooling air supply.
8) Record amplifier—input impedance 5000 ohms, input level 1–20 volts.
9) Playback amplifier—output impedance 600 ohms, output level 5 volts.

All of these performance requirements were met or exceeded by the equipment design being described here.

## System Description

Fig. 1 is a simplified schematic diagram of the tape system which was designed to satisfy these requirements. All four major system components are indicated, *i.e.*, heads, circuitry, transport (drive, guiding, tensioning, storage), and tape. It is self-explanatory and quite conventional except for the rotating playback head which scans the tape as it wraps around it on its path to the take-up reel. By this means, continuous frequency multiplication is obtained. You will note that the head's direction of rotation is arranged to maintain correct time sequence; *i.e.*, the information recorded first is played back first. To accomplish this, it is necessary to provide the head with a velocity vector such that it is opposite to the direction of the normal tape motion.

### *Wow and Flutter Reduction*

By far the most difficult requirement to be met in designing a tape system such as this one is the requirement for low wow and flutter. Although, as noted above, a significant reduction can be effected by using a reference signal which is required in the data-processing system, such compensation is exact for low-frequency components only. Furthermore, a conservative design requires a substantial safety margin reserved for the degradation that always accompanies long wear under adverse field conditions. For these reasons, the system design goal, without compensation, was established at an 0.2 per cent peak. Such performance would, on a normal transport operating at 1.875 inches per second, be quite difficult; with the high-speed rotating head, normal problems are compounded. Therefore, in considering the design of this system, it behooves us to examine the major sources of wow and flutter and to estimate, where possible, their magnitude. This has been done and the results are summarized in Table I.

The percentage frequency change, from all causes, may be written

$$df = \frac{100(dV/V_R - dS)}{1 + dS} \text{ per cent, where}$$

$dV$ is the speed variations from all causes other than long-term static changes, referred to the input (inches per second).
$V_R$ is the linear tape speed during record (inches per second).
$dS$ is tape elongation (inches per inch).

In deriving this formula, long-term changes due to tape expansion have been deliberately separated from all other changes which are implied in the term $dV$.

The first three sources listed in Table I can only cause long-term variations. This is particularly true of 1 and 2, which, because of the large thermal and humidity inertias and the considerable isolation afforded by the transport cabinet, can only change over the range indicated in time periods measured in hours. The total frequency change from these causes is 0.31 per cent. Because of its steady-state nature, this effect is reduced to insignificance by the compensation scheme mentioned earlier. It is interesting to note that if the transport is

TABLE I

MAJOR SOURCES OF WOW AND FLUTTER

| Source | Estimated Magnitude |
|---|---|
| 1) Tape expansion/contraction due to temperature changes. | $dS_t = 0.002$ inch per inch for a 100°F temperature change. |
| 2) Tape expansion/contraction due to changes in relative humidity. | $dS_h = 0.001$ inch per inch for a 90 per cent change. |
| 3) Tape expansion/contraction due to tape tension changes. | A) $dS_t = 0.000023$ inch per inch for tension servo-equipped transport.<br>B) $dS_t = 0.0015$ inch per inch for constant torque tape transport. |
| 4) Capstan eccentricity; capstan diameter = 0.498 inch, TIR = 0.0001 inch. | 0.02 per cent resultant peak flutter. |
| 5) Playback head eccentricity; head diameter = 1.970 inches, TIR = 0.0001 inch. | 0.005 per cent resultant peak flutter. |
| 6) Capstan shaft and playback head bearing fit. | None—bearings are assumed to be effectively preloaded. |
| 7) Capstan drive motor speed variations due to supply-line frequency instability. | 5 per cent peak wow reduced to 0.05 per cent by use of stabilized power supply. |
| 8) Playback head speed variations due to supply-line frequency instability. | 5 per cent peak wow reduced to 0.05 per cent by use of stabilized power supply. |
| 9) Transmission belt or gear train variations. | None—direct drives used. |
| 10) Torsional vibrations in capstan and playback head drive shafts, tape slippage and other variable friction effects, elastic vibrations, etc. | $X$ |

used in a controlled laboratory environment (temperature variations restricted to ±5°F, relative humidity variations restricted to ±10 per cent), the total contribution of these sources is reduced from 0.31 per cent to 0.042 per cent.

Item 10 is, of course, quite difficult to estimate and can only be controlled by careful design. As noted earlier, in order to provide at the outset a reasonable safety margin, 0.2 per cent flutter was selected as a maximum allowable limit due to all causes in the transport mechanism. Under these conditions, and assuming simple harmonic motion and worst-case phasing for like frequency components, we may write total flutter as follows:

$$(\text{flutter})^2 = (0.2 \text{ per cent})^2 = (0.02 + 0.05)^2 + (0.005 + 0.05)^2 + X^2,$$

from which

$$X = 0.17 \text{ per cent}, \quad \text{or} \quad 85 \text{ per cent of total allowable.}$$

The only practical way to accomplish such performance in a system like this is to minimize all potential sources of flutter by careful design and precise manufacturing. The following discussion will serve to illustrate how this was accomplished for the factors lumped together under Item 10 of Table I.

*Drive Train Variations:* As noted in Table I, in order to eliminate the possibility of speed inaccuracies and variations due to belt drives (which, for proper operation, depend on friction to produce differential belt tensions) and gear trains which are even poorer as regards velocity variations, both playback head and capstan assemblies are directly driven by synchronous motors. To achieve the desired multiplication ratio with a reasonable capstan diameter (an 0.5-inch diameter is about the smallest which one can use and still maintain reasonable tolerances on run-out), it was necessary to use a capstan drive motor with a low synchronous speed. The motor selected operates at 72 rpm when excited by a 60-cps supply. This motor, then, has 100 poles, and as you might expect from a machine of this sort, there is considerable "cogging" at the output shaft. The cogging rate is 120 times/sec, which corresponds to the rate at which pole pairs are "engaged" with the rotor magnet segments. A flywheel is usually employed to smooth out such effects. This is possible if the flywheel has large kinetic energy compared to the disturbance. Its kinetic energy is directly proportional to the product of its polar moment and the square of its angular velocity. Unfortunately, the combination of low velocities and a large motor-shaft cogging demand an impractically large (from the point of view of space and balance) flywheel. To solve this dilemma a compliant coupling is used between the motor and flywheel. The natural frequency of coupling and flywheel capstan is about 1.5 cps which yields a transmissibility of 0.00015 at 120 cps. The flywheel inertia, though low (0.53 in-oz sec$^2$), is sufficient to smooth out capstan speeed irregularities that are transmitted through this filter.

No damping is used on this system other than that inherent in the coupling and that provided by the air entrapped in the flywheel housing. No problems have been encountered during normal operation with the damping thus provided. However, because the system is bi-directional, the capstan direction must be reversed once every 13 hours of operation. At least 15 sec must be allowed for the capstan drive system to stabilize after the application of a reversal command. This period could be reduced by the introduction of a dampening fluid inside the housing.

The effects discussed here for the capstan transmission are present in the playback head system. However, because the velocity component of kinetic energy is 625 times greater in the latter system than the former, the design of the flywheel and the associated filtering system is far less critical.

*Frictional Effects:* Frictional effects are probably the most troublesome factor in designing any high-quality tape system. At worst they can, in the equipment being discussed, completely nullify an otherwise valid system design and at best, because of their unstable nature, they cause variations in system performance. All of these pitfalls are magnified by wrapping the tape 180° around the playback head. At this point, where the head is rotating at high speed, the danger of exciting elastic vibrations in the tape is quite large. Furthermore, because of the frictional effects the tape tension leaving the head would have to be three times that entering (assuming a coefficient of friction between head and tape of 0.3). As a result, the following additional problems would be encountered:

1) The difference in tape tension is equal to the friction force acting on the head periphery and this, if it is large, imposes considerable additional load on the driving motor and, more important, would result in the creation of significant differential elongation along the tape as it wraps around the head, causing changes in effective wavelengths and therefore inaccuracies in playback frequency.

2) If the friction force is large, the dielectric properties of the tape would permit the build-up of large electrostatic charges which will result in tracking, head contact and other tape dynamics problems.

3) The friction force itself will vary with environmental conditions, surface conditions, etc., which will produce variations in tape dynamics around the head and in system performance from day to day.

4) A large friction force combined with the high head speed will result in accelerated head and tape wear, head heating, and, possibly, pole piece displacements.

Fortunately, none of these effects have been noticed because an air-bearing with laminar flow exists in the tape head contact area, reducing the friction to a diminishingly low value. As one might expect, during starting, before the air-bearing has had time to form, the friction effects are quite evident. As a matter of fact, special precautions had to be taken to insure positive starting of the head assembly. The tape path design which was finally evolved, in which the Mylar side of the tape makes contact with the head, is particularly helpful in this respect.

The same solution must be employed to eliminate the adverse effects of friction in the remainder of the transport system, *i.e.*, to reduce the friction. At low tape speeds no inherent "friction-free" situations exist like the one described above. One must use care in minimizing the wrap around fixed posts and heads, use high-quality low-friction bearings, polish tape contact points carefully and make certain the available driving force is not marginal after allowance has been made for frictional variations. This applies to driving torques available at the reels and the capstan where, paradoxically, the drive depends on the friction force between the capstan and tape.

*Elastic Vibrations:* Elastic vibrations are variations in tape length with time caused by changes in tape tension. The variations can be cyclical or not depending on the excitation, the damping present and the tape geometry. They, quite obviously, result in wow and flutter if they occur in the area of the heads and/or capstan and the resultant flutter is inversely proportional to tape velocity. If they originate at a point outside the head area, they will be attenuated by damping in the tape itself and friction points in the tape path. The closed-loop capstan drive design commonly used on many high-quality instrumentation transports is effective in attenuating such vibrations when they originate outside the loop. Quite obviously, if they are to be avoided tension variations must be eliminated. This is accomplished by utilizing a high-performance tension servo which maintains tape tension constant. In addition, the reduction of friction in the tape path to the lowest practical value is a necessity. As already noted, friction is difficult to control and, since the tape tension must differ on either side of every friction point by the friction force, tape tension variation results which can lead, in turn, to elastic vibrations.

At this point, it is worthwhile to discuss what may seem a paradox. Friction in the tape path can be deliberately used to damp out elastic vibrations excited elsewhere. This practice has been quite widespread in the design of digital tape transports which must accelerate tape from rest, in milliseconds, to speeds in the order of 100 inches/sec. These accelerations often result in transient elastic vibrations which yield tape velocity changes as great as 25 per cent of the capstan velocity. Friction can be used to damp them; however, this is an exceedingly difficult design problem, particularly when one considers the variations in friction forces which result from "air-bearing" formation and loss as the tape is accelerated and decelerated at, for all purposes, random rates. As a result, there usually remain long-term velocity variations and uncertainties in the order of 1 per cent or so. While they can be tolerated in most digital systems, they are unacceptable in a system such as this. The other undesirable frictional effects noted above, of course, must also be tolerated in such systems.

Unbalanced rotating components in the tape path can produce flutter by a variety of mechanisms. Often neglected but nonetheless important are the capstan pinch roller(s), and rotating tape guides and idlers. Here, as in the case of friction, those located near the heads and capstan have a greater effect, because of damping, than those located remotely. None can be neglected.

### *Equipment Details*

*Packaging:* Fig. 2 is a photograph of a completed 14-channel system. As you can see, it is housed in a sealed dust-proof cabinet from which the front cover has been removed. In order to remove heat (approximately 750 watts is dissipated when the system is in operation) from this sealed cabinet, we utilized a water jacketed aluminum cabinet. An internal air circulating fan maintains operating temperatures while external air tem-

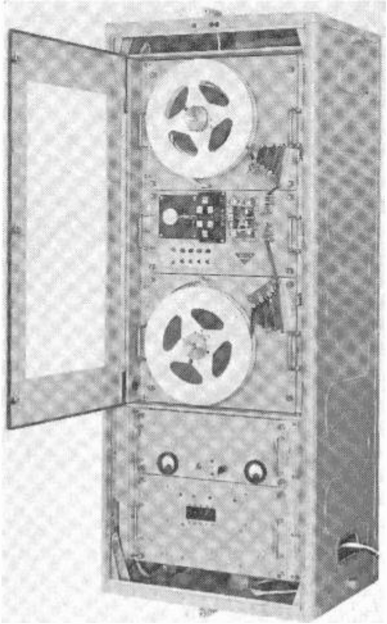


Fig. 2—Photograph of completed system with top dust cover opened and cabinet closure removed.

perature is 122°F, provided the inlet water temperature does not rise above 90°F.

The tape system proper is constructed of five separate modules. From top to bottom they are: upper reel drive, tape drive and head station, lower reel drive, read/write circuitry and stabilized power supply. Each module is mounted on heavy-duty ball-bearing slides and is designed for standard RETMA rack mounting. The electrical connections are made at the rear of each assembly and are accessible when the slides are extended to their outermost position. Under these conditions, the modules can be removed from the cabinet for servicing.

*Reel Drive System:* The reels are standard 14-inch-diameter NAB reels which hold 7200 feet of one-inch-wide Mylar tape. Captive reel hold-downs are utilized and tape pack followers must be included to signal "low tape" before the tape supply is exhausted. Assuming, for the sake of discussion, that the upper reel is the supply reel and the lower reel is the take-up reel, the tape moves from the upper reel through a spring-loaded dancer arm assembly, through the tape drive and head station assemblies, which will be described in detail later, past a second spring-loaded dancer arm assembly, and on to take-up reel. The spring rate of the dancer arm is quite low, so that as the arm is deflected only small changes in tape tension result. Directly coupled to the arm shaft is a magnetic transducer which is excited by a 5-kcps source and whose output is demodulated and used to control the firing angle of silicon control rectifiers. These rectifiers are arranged to provide full-wave rectification of the 60-cycle line voltage which, in turn, is used to control the split-field, reel-drive torque motors. The servo system has proportional plus derivative response and is extremely stable in operation. All rotating components in this drive system, including the rollers on the dancer arms, use specially selected precision bearings, have ground stainless-steel shafts and are homogeneous and/or balanced to eliminate the introduction of irregularities in the tape drive system.

The metered tape velocity is $1\frac{7}{8}$ inches/sec. The reel drive servo system will respond to a change in direction of tape drive and will stabilize and meet all system specifications after 20 msec. It also provides high-speed rewinds of 200 inches/sec average and is capable of reliably stopping the tape, without breakage or large tape tension transients, in 2 seconds from this speed. The rewind operation, including stop from rewind, is a reel-to-reel mode. That is, it is accomplished by introducing an error signal in one or the other reel servos and allowing the other reel servo to maintain constant tension while the tape rewinds—the capstan is not used for tape metering and stop is initiated by removing the error signal and allowing both servos to reach tape tension equilibrium.

*Tape Drive and Head Station Module:* Fig. 3 is a close-up of the tape drive and head station module. Assuming the tape is moving from the upper to the lower reel, as it leaves the last roller on the fixed roller bracket, it passes a double post conductive leader end-of-tape station, makes a turn around an idler roller, passes between the capstan and upper solenoid actuated pinch roller, passes through the tape brake station, and enters a fixed head assembly.

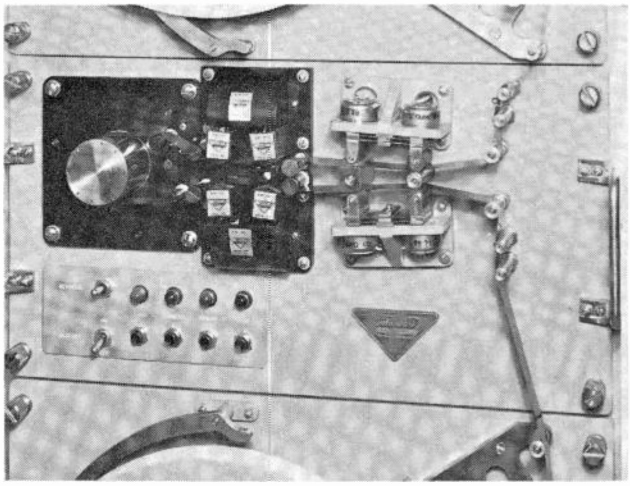


Fig. 3—Photograph of tape drive and head station module, front view.

This fixed head assembly contains two head stations. The first in the tape path is a full-tape-width erase station. The second head is a 14-channel, in-line record head stack. Both head stacks are mounted on a precision ground base plate which has integral post guides and head connectors. The complete assembly is field replaceable. Directly beneath the fixed head station is another station which is its mirror image; that is, the head stack immediately below the upper erase head is an erase-head assembly, and that immediately below the record head is a second-record-head assembly. A mu-metal shield is used between the two erase heads.

As the tape leaves the first fixed (record) station, it passes over a fixed post guide and wraps around a rotating playback head station where it makes "contact" for 180° (controlled by integral upper and lower post guides), then passes the lower fixed head station, tape brake station, capstan, lower solenoid pinch roller, turns around an idler, passes the lower end-of-tape station, and enters the lower reel dancer arm assembly.

Pertinent fixed head specifications are as follows:

| | |
|---|---|
| Gap scatter | ±50 microinches |
| Gap azimuth | 90° 00′±1′ |
| Gap length | 500 microinches for recording, 0.007 inch for erase-head gap |
| Track width | 0.032 inch |
| Track spacing | 0.070 inch |
| Contact angle | 90° 00′±1′ |

The order of engagement of the pinch rollers is important. The downstream pinch roller must be engaged before the upstream pinch roller in order to prevent the loss of tension of the tape head area. Thus tape tension on either side of the pinched rollers, except for friction, is controlled by the upper and lower tension servos.

The tape, as it turns around the playback head assembly, has its Mylar surface in contact with the rotating head. This arrangement reduces the friction between head and tape during starting and prevents the build-up of oxide on the rotating head surface. As a result, with the tape brakes engaged, it is possible to scan short segments of tape repeatedly for detailed analysis without danger of oxide rub-off which might damage the tape or cause oxide build-up across the playback head gaps. Manual controls and indicators, which are useful in loading the tape and during system checkout, have also been located on this module. These controls are over-ridden by remote command signals, when the dust cover is closed.

Fig. 4 is a schematic diagram of the rotating playback head assembly. You will note that there are two gaps, 180° apart, along its periphery which make contact with the tape during the playback. The head coils are connected in series and the construction is "hum-bucking." The physical gap length is 0.003 inch. The construction of the head assembly itself is quite conventional. The pole pieces are made of laminations 0.004 inch thick and they and the shields are set in an aluminum bracket similar to those used in conventional multi-channel head stacks. The pole pieces are 0.028 inch wide and 0.015 inch deep. The assembly is, of course, symmetrical about the axis of rotation and considerable care was exercised to provide a smooth surface to aid in the formation of a stable air-bearing. The necessity for maintaining low run-out has already been cited.

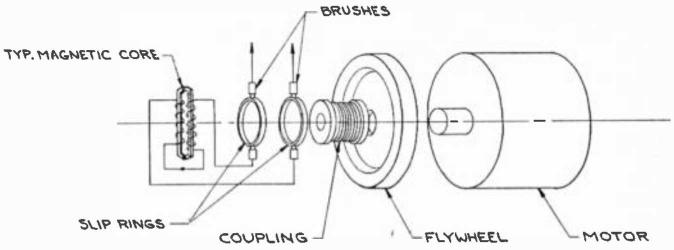


Fig. 4—Rotating playback head schematic.

The rather unusual geometry of the head structure results in a small volume available for windings. Therefore, despite the high readback tape velocity it has a relatively low output voltage. The slip-ring noise limited the over-all signal-to-noise ratio to approximately 35 db. During the development phase, insufficient time was available to decrease slip-ring noise and, thereby, to increase the signal-to-noise ratio. Theoretically, the signal-to-noise ratio should be the same as that obtainable with any high-quality tape system operating over similar bandwidths and/or recorded wavelengths—after corrections for separation losses, if any.

Fig. 5 contains output voltage oscillograms for sine-wave recordings. All patterns were made at a recorded frequency of 140 cps, with bias, and a recording speed of 1.875 inches/sec. This corresponds to a recorded wavelength of 0.0134 inch.

As one gap leaves the tape contact area and the other enters it, there is a discontinuity in the playback waveform. These may be observed in Fig. 5; the duration and shape of the discontinuity is a function of engagement angle. It will be noted that the duty cycle (defined as uninterrupted scan period divided by total period), is greater than 95 per cent when the engagement angle is adjusted properly. This is more than adequate for valid signal processing in the balance of the equipments.

Fig. 6 is a photograph showing the top view of the tape drive and head station module. At the left may be seen the playback head, slip rings (through access port), flywheel, coupling and drive motor. On the right-hand side is the capstan drive motor and coupling and flywheel housing.

Fig. 7 shows typical response curves for the tape, head, and bias compromises used in this system. Bias frequency was 5000 cps. Actual playback frequencies are 100 times the record frequencies shown on the abscissa. Constant-current recording was used and the resulting uncompensated playback characteristic of the rotating head assembly is shown as curve 1. The playback equalization required to obtain flat response over the system bandwidth is obviously quite simple. Curve 1 does not rise with a 6 db/octave slope (rises about 4 db/octave) because of the separation losses. The tape-head separation is due to two factors: 1) the air-bearing which causes approximately a one mil separation between the tape and head surface and, 2) the tape backing thickness which is 0.9 mil for the tape used. Curve 2 is a plot of the resultant separation loss.

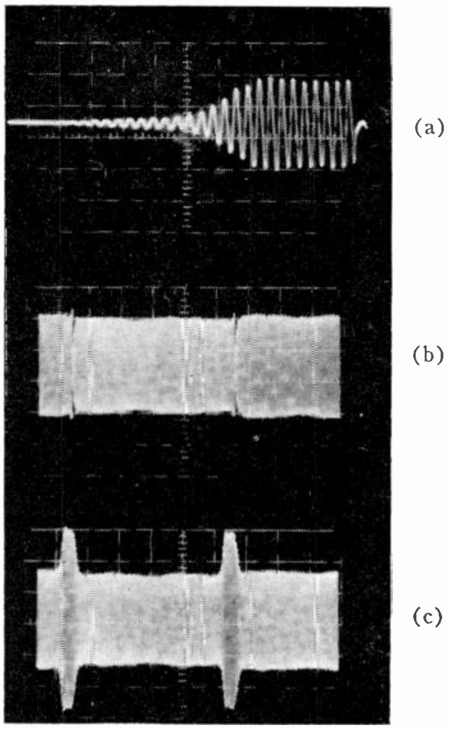


Fig. 5—Typical playback head waveforms. Recorded frequency—140 cps. Recorded wavelength—0.0134 in. (a) Tape engagement angle $<180°$ sweep—200 $\mu$sec/cm. (b) Tape engagement angle $=180°$ sweep—2.5 msec/cm. (c) Tape engagement angle $>180°$ sweep—2.5 msec/cm.

Head frequency and tape thickness losses (tape coating thickness is 0.35 mil) are negligible. As a result, the uncompensated head output curve peaks at a wavelength which is slightly more than twice the physical gap length. In normal analog practice thickness losses are appreciable and peaking occurs at wavelengths which are a much higher multiple (8 to 10 times) of the playback gap length.

Curve 3 is the head output response with the oxide turned in toward the head surface. Under these conditions, the separation losses are to the air-bearing only. As a result of the decreased head to tape spacing, the curve peaks at a higher frequency and, in the long wavelength region, the slope is somewhat steeper—approximately 5 db/octave. The losses are, of course, less and the output therefore, at all frequencies, would be higher than that for the tape as used. For example, at 150 cps, the output would be approximately 4 db greater than the output for the oxide reversed case. The figure also contains a plot of calculated head output if there were no separation losses at all; *i.e.*, if no air-bearing existed and the oxide was turned in. The curve is derived by adding the curves 1 and 2. You will note that the curve rises with a 6-db/octave slope and its peak is, again, shifted to the right.

The physical gap length was chosen so that the head responses peaks in the center of the system bandwidth. As a result, the long gap is available for higher output and manufacturing problems are less critical. Head wear is not a problem because of the "friction-free" operation resulting from the air-bearing. Obviously, if longer wavelengths were used, the separation losses would be smaller. This factor, coupled with the high playback velocities, should result in usable signal-to-noise ratios at the low end of the spectrum. There are three important reasons that dictated the selection of recorded wavelengths:

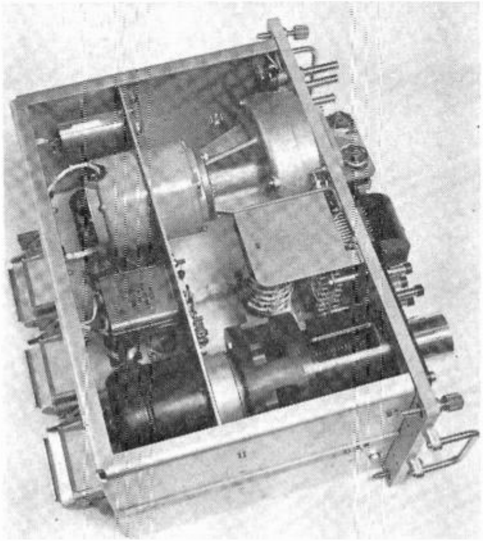


Fig. 6—Photograph of tape drive and head station module, top view.

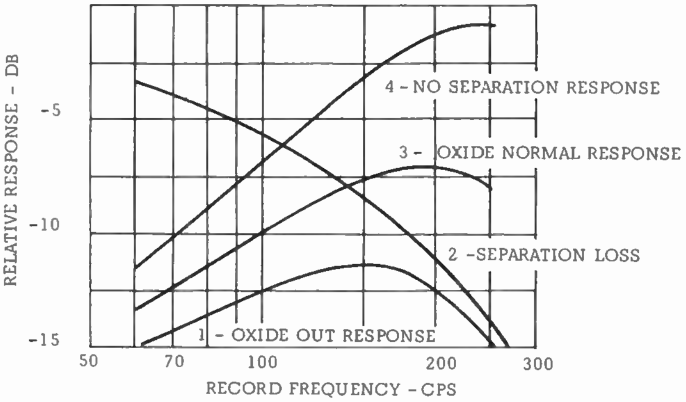


Fig. 7—Equalization curves. Record speed—1.875 inches/sec Playback speed—187.5 inches/sec.

1) Increasing the wavelength would require higher tape speeds which, in turn, for the same recording period, require proportionately greater tape storage capacity. The present system, operating 1$\frac{7}{8}$ inches/sec, uses 14-inch-diameter reels, which are the largest reels considered practical for this application.

2) If significantly longer wavelengths were used, "contour effects," particularly with the tape wrapping 180° around the playback heads, would cause aberrations in the output response.

3) The present system, which utilizes conventional

wavelength tape-speed relationships, records the raw data so that it can be played back in its original form on standard instrumentation recorders. Furthermore, the playback equalization necessary to correct the separation losses is trivial when compared to the accessibility and the value of the information thus preserved.

*Read/Write Electronics:* The read/write circuitry is conventional for analog recorders. Only solid-state active devices are used here and in the rest of the equipment. All circuit components are mounted on glass epoxy, plug-in printed circuit cards. The read/write module, which contains 14 channels of electronics including bias/erase oscillator and buffers, voltage regulators and input/output monitors is the fourth from the top in Fig. 2. Fig. 8 is a top view showing all cards in position. Note that the test points and adjustments are accessible with the drawer open. As is conventional in instrumentation recording systems, constant-current recording is used. The playback chain used to provide flat (±1 db) response over the pass band is the mirror image of curve 1, Fig. 7. The importance of forming a *stable* and *repeatable* air-bearing can be appreciated by comparing the differences in required equalization for curves 2 and 3 of Fig. 7. The precise tape-tension control made possible by the tension servos and low tape path friction are primarily responsible for our success. The playback amplifier is designed to fall off at 12 db/octave outside of the system pass band.

*Stabilized Power Supply:* The bottom module in Fig. 2 contains the stabilized power supply. Fig. 9 is a closeup of this unit. It generates the 117-volt ± 10 per cent, 60-cps ± 0.05 per cent power which is used to power both the playback head and capstan drive motors. The all-solid-state device uses a 480-cps tuning fork whose output is divided by eight and then amplified by Class-B amplifiers. Power output is approximately 100 watts with a 0.8 factor load. The unit uses a 20-volt collector supply and transformer output. In order to reduce the filtering problems for this low-voltage high-current load, we elected to use the three-phase power available. The design is conventional and extremely conservative, with all components operated well below manufacturer's ratings.

## CONCLUSIONS

This equipment has been operating in the field for six months and is reliably producing signal processing improvements greater than originally envisioned. The operating performance obtained demonstrates conclusively that magnetic recording techniques can, in addition to storing large amounts of raw data, provide accurate and stable frequency multiplication with system linearity and a short (and easily controlled) processing delay. Furthermore, it has been possible to scan short sections of data at high speeds and in real time repeatedly, thus making practical time sharing of the balance of processing equipments. This technique is by no means limited to the frequency spectrum and bandwidths utilized in the subject equipment. To persons skilled in the art, many applications in data-processing systems—particularly in correlation equipments—will suggest themselves.

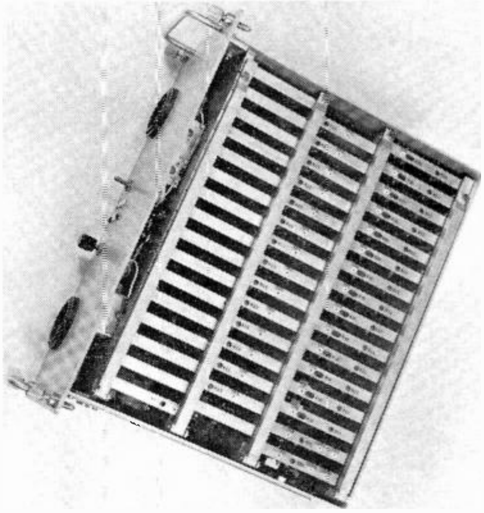


Fig. 8—Photograph of read/write module.

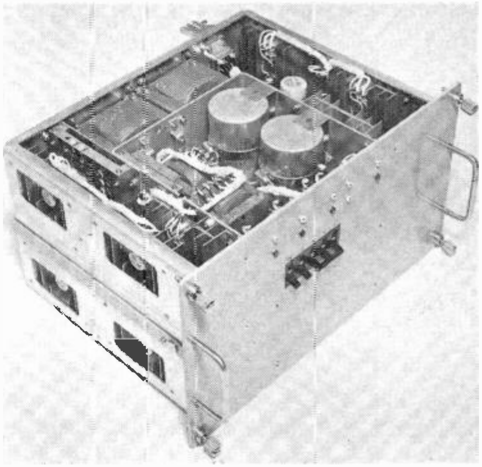


Fig. 9—Photograph of stabilized power supply module.

## ACKNOWLEDGMENT

The author wishes to acknowledge particularly the efforts of Francis P. MacGowan of the Cook Electric Company for his management of the active equipment-design phase of the project and for many contributions to the over-all design; Robert C. Wahrer of the Cook Electric Company for contributions made in the testing and debugging phases; and Beverley R. Gooch of the Clevite Corporation for his contributions to the design of the rotating playback head assemblies.

# Information Storage Density of Magnetic Recording and Other Systems*

MARVIN CAMRAS†, FELLOW, IRE

*Summary*—**Information storage density in bits per cubic centimeter are compared for various media including magnetic tape, phonograph records, photographic film, the human nervous system, and biological genetics. Magnetic recording is on a par with other man-made systems; but all of these are poorer by many orders of magnitude than genetics. An analogy between contact printing of tapes and genetic replication shows the superiority of the latter. Factors which limit the ultimate density of magnetic recording are discussed: gap-length, straightness, shunt effect, azimuth; tape surface, stability, particle size; head-tape contact, drive stability; amplifier noise, and demagnetization.**

BEFORE you have worked long in magnetic recording, somebody is sure to ask, "Why can't you get the same results at half the speed?" This always happens no matter how slowly you are going at the time.

We can reply by asking, "Why don't they slow down movie films and disk records? Why aren't microfilm pictures smaller? Why can't they print an encyclopedia on the head of a pin?" All these are special cases of the general question of how much information can be stored in a given length, area, or volume. It turns out that magnetic recording compares quite favorably with other media, as shown by Fig. 1.[1]

We may next examine magnetic recording to find what obstacles, if any, are encountered by further progress. It is logical to expect that the more mature recording arts chose their present format not only for maximum information storage, but also for economy and convenience. Most of them can achieve better storage density if they are pushed; but the expense, criticality, and reliability may be increased out of proportion to the benefits obtained.

Are we presently operating near an optimum point in magnetic recording? Or should we be operating at densities nearer to the 100,000 cycles per inch predicted by Brophy?[2] It is instructive to project the requirements of a 100,000 cycle per inch system in terms of known behavior of magnetic and mechanical elements:

*Head Gap Length:* A null point (zero output) occurs when the effective gap length equals the wavelength. A gap about half this size is operative, so we require a gap length not over 5 microinches (⅛ micron or 1200 angstrom units).

*Head Gap Straightness:* Departure of the recording slit from a straight line by over 5 microinches is similarly detrimental for interchangeable recordings, but can be self-compensating if the record is made and played on the same machine. Even on the same machine the tape can shift laterally between recording and playback sequence, so that the recorded wave no longer matches the head.

*Head Gap Shunt Effect:* Only a fraction of the recorded flux threads the pickup coil. Even with gaps of about 0.1 mil, much of the flux is lost across the facing area of the confronting polepieces (neglecting eddy currents in the gap spacer). To minimize this effect, the depth of polepieces is reduced, but at the expense of head life. With a 5-microinch gap, the facing area cannot be reduced in proportion, and a loss of roughly 20 db can result.

*Azimuth Alignment:* During playback, any tilt between the head and recorded wavelength causes loss of short wavelength response. An error of 5 microinches from edge to edge of the scanned track is the maximum tolerable, so when a head 0.0625 inch wide is used the angle becomes $0.000005/0.0625 = 0.00008$ radian, or about 15 seconds of arc. An error of this magnitude occurs if the tape shifts 0.0004 inch laterally at a guide 5 inches from the head. Commercial tapes themselves may have 0.006 inch tolerance in their width, or 15 times greater than the cumulative amount permissible.

## CONTACT PROBLEMS

Playback loss due to separation between tape and head is given by:

$$\text{playback loss,} \quad \text{db} = 55 \frac{\text{separation}}{\text{recorded wavelength}} \cdot \qquad (1)$$

Recorded loss is at least as great, so that a conservative estimate is:

$$\text{over-all loss,} \quad \text{db} = 110 \frac{\text{separation}}{\text{wavelength}} \cdot \qquad (2)$$

If variations at our shortest wavelength are to be less

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*Received by the PGA, March 27, 1961. Appeared as "Magnetic Recording of Short Wavelengths Research" in the 1961 IRE INTERNATIONAL CONVENTION RECORD, pt. 2, pp. 74–80.

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

[1] This chart is intended only to give an idea of order of magnitude, based on estimates of the average state of the art, or as otherwise noted. There is always a question of what may fairly be chosen as "average," and what fraction of the total record package is essential to its information content. Therefore, any close agreement with other estimates is purely coincidental. Examples may be found in each form of recording that could move its position up or down on the graph. However, because the vertical scale is logarithmic, it takes quite a bit of improvement to move up even one notch. For example, if we improve tape recording to an extent where 1⅞ inches/sec is equivalent to former 7½ inches/sec. the indicator on Fig. 1 would increase slightly more than half a division.

[2] J. J. Brophy, "High density magnetic recording," IRE TRANS. ON AUDIO. vol. AU-8, pp. 58–61; March–April, 1960.

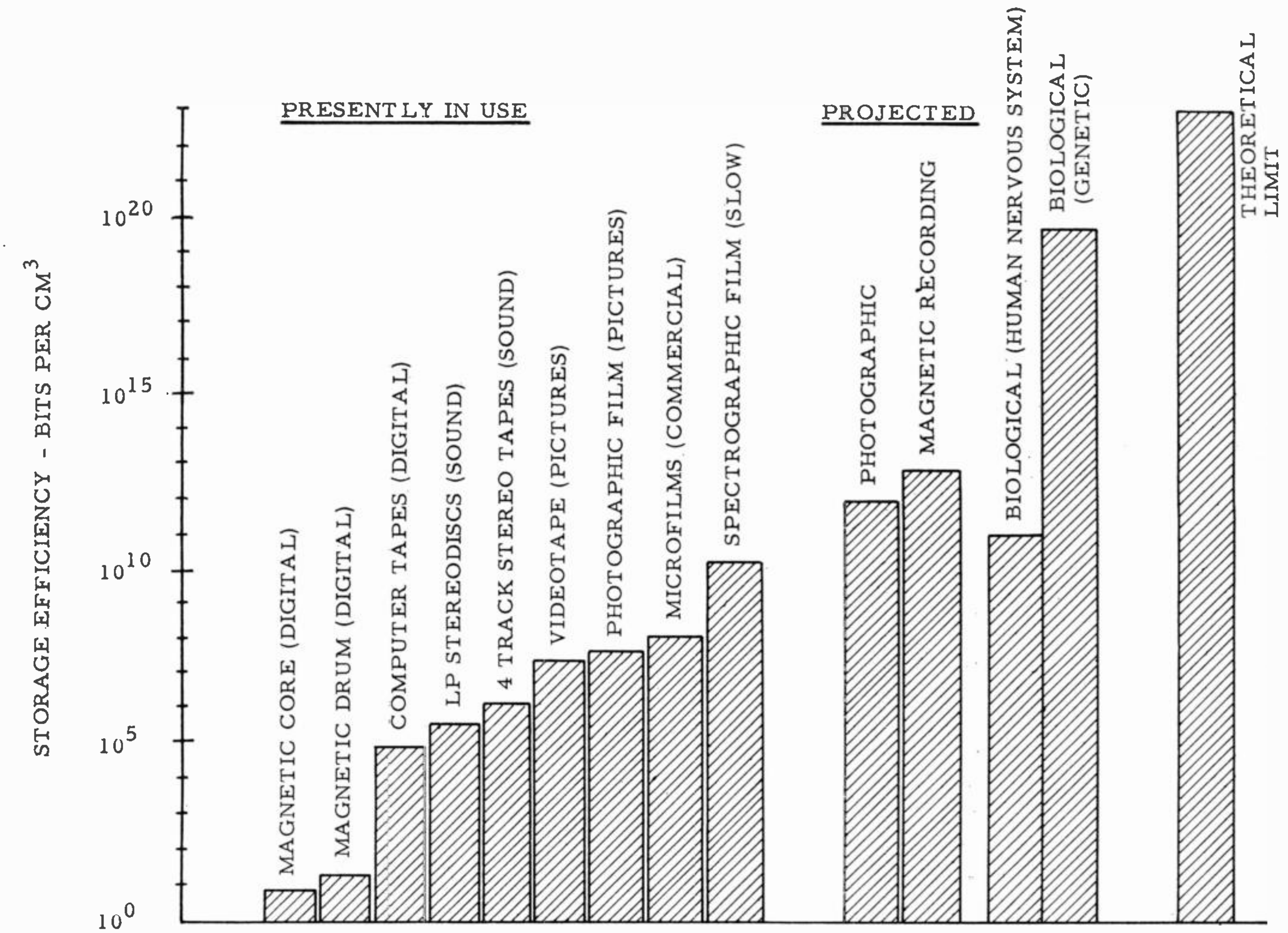

Fig. 1—Information storage capabilities of common recording systems.

than 6 db, the greatest permissible spacing is about 0.5 microinch (1/80 micron or 120 angstrom units). This is 2 or 3 orders of magnitude smaller than what is ordinarily considered a smooth surface.

At speeds of 100 inches/sec or higher, the formation of an air cushion between tape and head was noted by several observers. A similar effect has been observed even in a vacuum, which leads one to expect that "bouncing" of high spots on the tape against the head causes the tape to assume an average spacing at speeds where its mass and springiness prevent detailed conforming with the head.

After repeated use, a roll of tape picks up dust and dirt even under best conditions. Where a fraction of a micron is bothersome, the slightest trace of foreign matter results in erratic behavior of output and frequency response.

*Tape Surface:* In keeping with the foregoing specification, the tape surface should be smooth within 120 angstroms, which is better than the specifications for optical surfaces. This need occur only over an area where the tape contacts the gap.

*Tape Stability:* Tape wound on a reel is under tension of a few ounces to a pound or more. If kept in this condition for any length of time, and especially through excessive temperature or humidity cycling, plastic flow occurs, and uneven warpage takes place. When such tape is played back the warpage can result in momentary azimuth error, lateral displacement, and loss of contact. Where a few microinches are important an imperceptible warping may be troublesome.

*Tape Particle Size:* The micron particles in present-day tapes are able to resolve a shorter wavelength statistically across the width of the gap. However, a much finer grained material is desirable, and this has to be dispersed with greater care. A practically continuous metallic film made by evaporation may be one approach.

*Drive Stability:* For audio work, high-density recorded tape is driven at tenths of an inch per second. At very low speeds conventional drives do not store enough energy to stabilize the tape. Also, tape stretch, vibration, and warpage are more harmful than at ordinary speeds. It is not simple to design a moderately priced drive that will maintain wow and flutter limits of 0.2 per cent under such conditions.

*Amplifier Gain and Noise:* Very low output is obtained at high recorded densities because of self-demagnetization, head gap shunting, and the thin recorded layer. An optimistic estimate assuming linear proportionality is a 34-db signal loss in going from 2000 cycles per inch to 100,000; head losses might easily lower the signal another 20 db. We are then operating uncomfortably close to noise levels, such as Johnson noise which is inherent in amplifiers and circuits.

*Erasing of Short Wavelengths:* Even if the gap size could be reduced to zero, it would not define a perfectly sharp field throughout the thickness of the record. Because of this, a recorded short wavelength is not entirely beyond the influence of the field immediately after leaving the gap, but is subjected to one or more reversals of the bias field and the signal field. Such effects may be remedied by special heads using the *X*-field principle.[3]

The above requirements may be classified into:

1) *Greater mechanical precision* in tapes, heads, guide systems, and transports.
2) *More efficient head design* and construction.
3) *Better amplifiers.*

Mechanical precision is by far the most severe limitation, and this is usually expensive. It appears that the higher densities achieved in recent years have been a result of better mechanical techniques, rather than new principles of recording.

## ULTIMATE LIMITS OF RECORDING DENSITY

Eventually one would expect the granular nature of matter to set an ultimate limit to information storage which depends on the position of particles, or their magnetic, electrostatic, or chemical state. For example, a cubic centimeter of iron contains about $10^{23}$ atoms.[4] If the electron spin in each atom could be set in a prearranged pattern of plus or minus magnetic moments, a cubic centimeter would hold $10^{23}$ bits of information. This is an unrealistically high upper limit, but it is interesting to compare it with practical storage capacities.

In tape recording of sound, densities of about 800 wavelengths per cm (2000 per inch) are commercially achieved, corresponding to about 1600 bits per cm.[5] On this basis, the popular quarter-inch-wide four-track tape presently used for stereo has $10^4$ bits per square cm. The tape winds about 300 layers per cm, giving $3\times10^6$ bits per cubic centimeter (cc).

It is interesting that a stereo LP record has a recorded density comparable to that of four-track tape. Considering both sides of a stereorecord at 300 lines per inch, the record carries $8\times10^5$ bits per cc. (The inactive area was not considered.)

The figures can be improved both for tapes and for phonograph records if we are interested in maximum volume-density of information. The thickness dimension can usually be decreased most readily, and the number of recorded lines increased. By recording 500 tracks per inch on magnetic tape, Eldridge and Babba[6] were able to obtain 155,000 bits per square cm (1,000,000 per square inch). With the thinnest commercial tape of 0.0025 cm (0.001 inch), we can pack 400 layers of 155,000 bits per layer into a cubic centimeter to give $6.2\times10^7$ bits per cc.

At the other extreme, digital computers which require almost perfect reliability have until recently used only about 200 bits per linear inch,[7] with 14 tracks per inch. At 435 bits per square cm and 200 layers per cm, there are $8.7\times10^4$ bits per cc. Core memories and drum memories have a considerably lower density of information.

Projecting into the future, and making an optimistic estimate,[1] we might record 40,000 bits per linear cm. If we could achieve this density on an area basis,[8] we would have $1.6\times10^9$ bits per square cm. With tapes of 0.00025 cm, one-tenth the present thickness, the recorded density becomes $6.4\times10^{12}$ bits per cubic cm, an improvement of $10^5$ over the present.

How does this compare with photographic systems? Ordinary camera film may record 700 bits per cm in both directions, or about $5\times10^5$ bits/cm$^2$. Again the thickness dimension (as in other forms of records we have discussed) is inefficient, so with an 0.012-cm thickness of movie film we obtain $4\times10^7$ bits/cm$^3$.

Commercial microfilm is about two or three times better, giving $10^8$ bits per cc under good conditions.

The highest photographic resolution with Lippman emulsions or spectrographic films is about $10^4$ bits per cm, giving $10^8$ bits per cm$^2$. The film thickness might be reduced to 0.00025 cm for a volume density of $4\times10^{11}$ bits per cc.

Video tape records about $8\times10^6$ wavelengths per second on a 15 in length of 2 in tape, or about $2\times10^7$ bits per cc for a 250 layer per cm tape.

Thermoplastic recording[9] is said to be capable of about $6\times10^5$ bits per square cm, or about the same as photographic film.

Tape and film storage capacity is quite remarkable. For orientation one may take the estimate by Brillouin[10]

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[3] M. Camras, "A new magnetic recording head," *J. SMPTE*, vol. 58, pp. 61–66; January, 1952.

[4] A cc of most other solid materials also contains roughly $10^{23}$ atoms. There is some variation, with the lower density materials not being packed quite as closely.

[5] From Shannon's Theorem we have the relation

$$\text{bits per second} = \text{cps}\left[\log_2\left(1+\frac{\text{signal}}{\text{noise}}\right)\right].$$

At a signal-to-noise ratio of three (10 db), which is reasonable at the upper frequency response limit, the factor in the brackets becomes two. A marginal system where the noise equals the signal has a factor of one, while a better system with a signal-to-noise ratio of 20 db has a factor of about three.

[6] D. F. Eldridge and A. Babba, "The effects of track width in magnetic recording," IRE TRANS. ON AUDIO, vol. AU-9, pp. 10–15; January-February, 1961.

[7] Some of the newer machines may go to a 555.5 bit per inch standard.

[8] Playback of such a record by ordinary heads would be no mean achievement, since a track $10^{-5}$ inches wide gives an output 80 db below that of the usual half-track.

[9] "Many applications await thermoplastic recording," *Electronic Design News*, p. 4; February 17, 1960.

[10] L. Brillouin, "Science and Information Theory," Academic Press, Inc., New York, N. Y., p. 289; 1957.

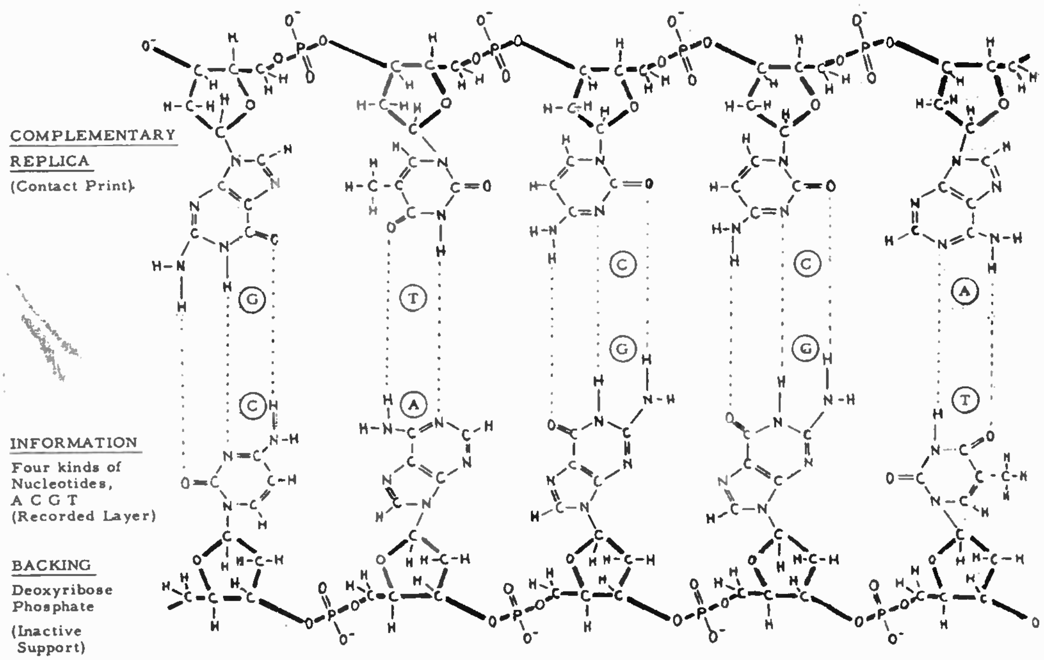

Fig. 2—Primary structure of DNA. Lower portion spells out "CAGGT" with a four-letter alphabet. Upper portion is its replica. Analogous to magnetic recordings, and duplication by contact printing.

that the amount of information contained in the entire American telephone system at any given instant of time is in the order of $4 \times 10^9$ bits. This could all be stored in only a cubic millimeter of our best media described above. We would need good access time, as the information is changing constantly, and this would require an elaborate and bulky read-out and read-in system.

We notice that information condensation is not the only factor in the size of a useful system. Access time is also important, and it seems that the greater the storage efficiency the poorer is its accessibility. In Fig. 1 the magnetic core system has the poorest storage efficiency, but an access time of about a microsecond. At the other extreme we might take the theoretical limit of $10^{23}$ atomic bits per cc. The most compact readout system would be a single channel, reading the bits serially. If the scanner could move with the speed of light it would take 30,000 seconds or nearly nine hours to read the most remote bit.[11]

The access time can be shortened by increasing the number of channels, but now the reading system becomes large, for there is a theoretical as well as a practical limit to the small size of a scanner, connecting wires, etc., required by each channel. One begins to expect that the quotient of storage efficiency and access time has significance.

$$K = (\text{bits per cc})/(\text{access time in sec})$$

and it may turn out that $K$ is related to one of the universal constants, as Planck's constant, when the other terms are expressed in a proper system of units.

## Biological Systems

If experience is a good teacher, then we might look towards biological systems for storage efficiency, since biological systems have had more years of experience with miniaturization than most people. Some very impressive examples are the brain and the genetic system.

We know that the genetic information for duplicating a living organism is contained in chromosomes of very small dimensions. This information specifies the construction of some $10^{12}$ cells and their physical location and connection to one another. Each cell by itself is complex, being made of many organic molecules.

Recent work[12,13] indicates that the genetic information is coded in the long chain-molecule of a substance called deoxyribonucleic acid (abbreviated DNA). Each bit is represented by a pattern of 12 or 14 atoms.[14] This may be verified in Fig. 2. As with other record media, the geometric form "wastes" a certain amount of space. Additional volume is needed to support and to preserve the record so that it can be useful, and there is probably some redundancy to increase the reliability. Estimating the efficiency at only 1 per cent, we take up about 3200 atomic spaces per bit, to give about $3 \times 10^{19}$ bits per cc, as shown in Fig. 1. Therefore, in respect to packing density of information, biological genetics is about a billion times as efficient as magnetic recording.

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[11] In fact, a single line of $10^{23}$ atoms would be six billion miles long, and would span the diameter of our solar system.

[12] A. Kornberg, "Biologic synthesis of deoxyribonucleic acid," *Science*, vol. 131, pp. 1503–1508; May 20, 1960. (1958 Nobel Prize lecture.)

[13] J. Lederberg, "A View of Genetics" *Science*, vol. 131, pp. 269–276; January 29, 1960. (1958 Nobel Prize lecture.)

[14] In the four-letter nucleotide code ACGT: Adenine (A) contains 14 atoms, Cytosine (C) contains 12 atoms, Guanine (G) contains 14 atoms, and Thymine (T) contains 14 atoms.

The human nervous system, including the brain, does not do nearly as well. Here, if we assume that the number of bits which a particular neuron may store is of the order of the number of synaptic connections, we have a total storage capacity of about $3\times10^{13}$ bits, divided among some $10^{11}$ neurons, each averaging about 300 bits. With the volume of the nervous system estimated at about 300 cc, the storage efficiency is $10^{11}$ bits per cc. Referring to Fig. 1, this is about 10 times as good as the best commercial method presently in use, and 1000 times as good as ordinary microfilm. However, the nervous system is exceeded by photographic and magnetic recording storage which are projected as being in the realm of possibility.[15]

The mechanism of storage and of duplication in biological genetic systems has features analogous to those found in the much cruder magnetic, optical, and mechanical systems today. As seen in Fig. 2, a strong backing of deoxyribose phosphate exposes a series of carbon atoms which have an attractive affinity for certain nucleotides. Any one of the four nucleotides A, C, G, or T may be attached to the carbon in a sequence that spells out the required genetic information. This is analogous to a magnetic tape which has a strong inert base layer of mylar and a coded message on the active surface. In the lower part of Fig. 2 we have represented the coding CAGGT.

It happens that the exposed portion of the nucleotide G forms an atomic template that can fit into the exposed portion of C, but will not fit anywhere else. This fitting is aided by separable hydrogen bonds shown by the dotted lines linking the coding to the complementary replica in the upper part of Fig. 2. The other side of each nucleotide is bonded strongly to its respective base, and will not separate. Similarly, the exposed portion of A will fit only with T. The complementary replica spelling GTCCA is the "negative" of the lower recording. Both really carry the same message.

Fig. 3 is a portion of a molecular model of DNA, showing how the paired recordings are wound into a helix. The dark shaded atoms form the strong inert backbone, while the lighter shaded atoms carry the coded information which fits only in complementary pairs. A complete molecule is a long helical chain of about 10,000 pairs, each pair having about 64 atoms. Its four letter alphabet thus carries 20,000 bits in duplicate form.

The chain molecule duplicates itself by untwisting while it is immersed in an environment of raw materials. This is pictured in the lower part of Fig. 4. Near portion 2, the original double-helix has unwound into two parts, breaking at the weak hydrogen bonds and exposing the coded templates to the environment. The exposed nucleotide templates will then attract their mates plus a backbone; and soon we have two perfect duplicates

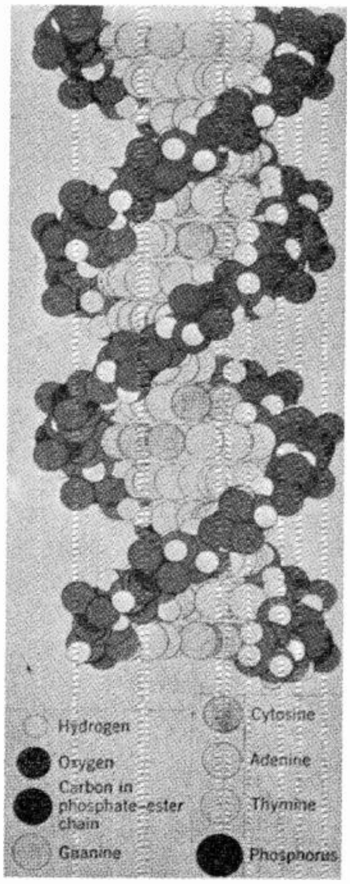
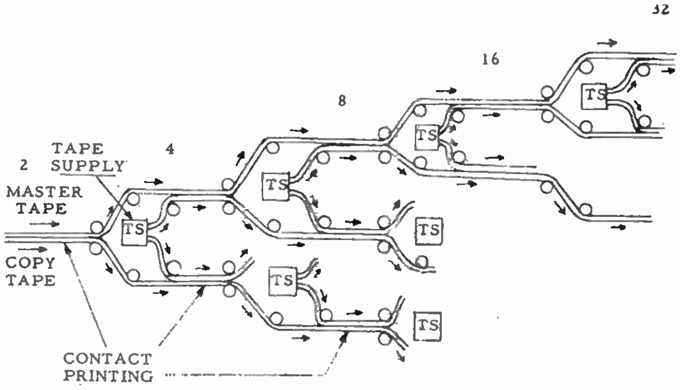
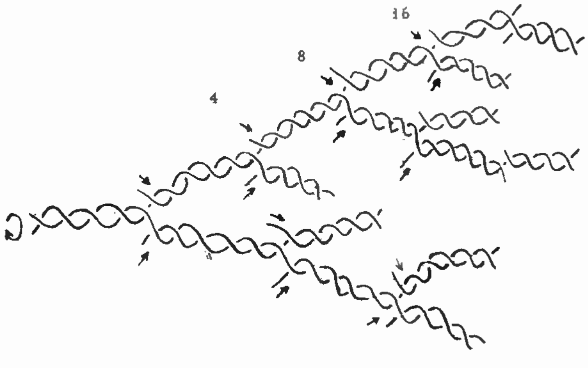


Fig. 3—Molecular model of DNA (after Feughelman[7]).[12]



TAPE



DNA

Fig. 4—Tape duplication system by contact printing, analogous to replication of DNA.[7]

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[15] Access time has not been considered. Accessibility comparable to that of the nervous system would require a rather tremendous volume of auxiliary equipment in magnetic or photographic storage.

of the original pair. Eventually the duplicates unwind as at 4. Each strand again acts as mold for casting a new replica from bits and pieces of its surroundings.

The analogous contact printing duplicator for tapes is shown at the top of Fig. 4. In this case, master and copy tapes of the same material are placed in contact and subjected to an ac field of the proper magnitude as explained in a previous paper.[16] Both tapes will now carry the recorded pattern, and after separation both can serve as masters to imprint a supply of blank tape in the region 4. The process repeats at 8, 16, 32, etc., with the number of records doubling at each step.

Those who have experience with tape duplicating of music will notice a fatal shortcoming in the tape duplicator of Fig. 4. Every slight imperfection in every stage becomes a part of the new intelligence, and the result is reduplicated in successive generations, each one adding new errors. After a few generations the original intelligence will be lost in a sea of noise. For the system to work properly, certain elements or combinations of these should be present: 1) a high degree of reliability, 2) regeneration of the data at each stage, and 3) rejection of erroneous recordings.

The DNA biological system avoids limitations of the tape duplicator by the use of a digital code. The nucleotide (A), for example, is a definite atomic arrangement which is as fresh and sharp at the millionth generation as in the original. It regenerates the pattern at every stage, so we cannot have a gradual deterioration but only a complete error, or omission. The template action appears to be almost errorless, and this is coupled with rejection of imperfect records.[17] Perhaps an engineer will be impressed with the reliability of the operation if it is pointed out that it has maintained itself continuously on the earth for about a thousand million years.[13] (Not many competitors can make this statement.)

When we compare the genetic process with man-made recordings in other respects, the elegance of the former is even more remarkable. In recording tapes we are trying to make the surfaces more perfect and the coating more homogenous and free from impurities. The DNA system avoids this completely. Geometrical perfection does not have to be generated by machines, but is inherent in the structure of the molecules. Impurities can be tolerated in the environment; these are not used since they do not fit anywhere.

Before the sales department gets carried away, we should indicate that quite a few engineering details must be solved before the principles can be applied to a recording system of the kind we use at present. However, it is interesting to speculate on the implications if something of the sort were extended to a complete recorder, rather than to the tape alone.

Instead of assembling tape recorders we might grow them from seeds; which would be the last word in automation. One could say with literal correctness, "This year, let's farm out our recorder business." Manufacturing problems would turn into agricultural problems, and the government might pay us for not producing a surplus.

## CONCLUSIONS

We started by asking why magnetic recording does not record more compactly. We found that this problem was not unique to magnetic recording but was common to all methods of storing intelligence. A comparison of known methods showed that magnetic recording ranked at or near the top. Projecting the requirements of even higher densities using present systems it was shown that we would have to pay an expensive price in high precision or low reliability. We then examined a mechanism by which living systems achieve a far greater storage density; and speculated on implications to man-made systems.

It is appropriate to repeat the statement by Dr. Lederberg, who received the Nobel Prize for his work in genetics. "If the ingenuity and craftsmanship so successfully directed at the fabrication of organic polymers for the practical needs of mankind were to be concentrated on the problem of constructing a self replicating assembly along these lines, I predict that the construction of an artificial molecule having the essential function of primitive life would fall within the grasp of our current knowledge of organic chemistry."

## ACKNOWLEDGMENT

The author is indebted to Scott Cameron of Armour Research Foundation for his helpful suggestions.

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[16] M. Camras, and R. Herr, "Duplicating magnetic tape by contact printing," *Electronics*, vol. 22, pp. 78–83; December, 1949.

[17] Errors which result in an improvement over the original are allowed to pass. Those mutations which have a high survival value will, in principle, gradually improve the successive generations.

# Correspondence

## Comments on "Enhanced Stereo"*

I read with interest Benson's article,[1] which itself was very interesting, but I take strong exception to the diagrams indicating multiple microphone placement. In the 1920's it was broadcast practice to use as many as six microphones feeding into a single monaural amplifier. The reproduction was very artificial, the quality being dependent on the skill of the technician operating the microphone padders. The results were sometimes fair but, more often than not, the quality was atrocious. With the advent of FM in the late 1930's, quality capabilities were enhanced to such a point that it was found that the artificial reproduction encountered by the use of multiple microphones was intolerable. FM pickups of the NBC symphonies and the New York Philharmonic and others were enhanced when only one microphone was used. The better FM broadcasters used this new technique, but some of the old-timers, in order to insure reliable operation and pickup of individuals, continued to use the multiple-microphone technique. In Buffalo the quality of live concerts of the FM channels is very poor in comparison to the Boston and New York areas. The reason is that in Buffalo they insist on using multiple microphones even in this day and age.

In picking up a large symphony for stereo operation, I have held to a single microphone per channel with excellent results. The addition of a third microphone, however, as outlined in the article, if done properly, would be highly desirable and particularly where soloists are used in the center of the stage, to eliminate the "hole in the center." The same arguments can apply to the use of a center speaker in playback. However, the minute the left and right channels use multiple microphones, we will have quality that is in effect two single monaural channels using techniques that became obsolete in the late 1930's. I have never found a technician or an engineer who could properly pad multiple microphone installations per channel to give "live" results. If this is used in an attempt to improve the reproduced music over the original, then the technique is doomed to eventual failure. Since sound arrives at different parallel microphones at different times and is reproduced in a single speaker and since the different arrival times cannot be separated, the result is far from realism. Such a system would be like trying to listen to a live concert (using six mikes) with six ears.

With many years of experience in this field where my ultimate goal has been realistic and accurate reproduction of the original, I can assure you that the use of multiple microphones in each channel can never accomplish the desired result. The only way this can be done is by the use of single microphones with single amplifiers for each channel. I am now an advocate of trinaural, and nothing less will ultimately be satisfactory.

H. K. MacKechnie
185 North Long St.
Williamsville, N. Y.

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* Received by the PGA, August 21, 1961.

[1] R. W. Benson, IRE Trans. on Audio, vol. AU-9, pp. 63–65; May–June, 1961.

# Contributors

B. B. BAUER

Benjamin B. Bauer (S'37–A'39–SM'44–F'53) was born in Odessa, Russia, on June 26, 1913. He received the E.E. degree from the University of Cincinnati, Cincinnati, Ohio, in 1937.

In 1923 he joined Shure Brothers, Inc., Chicago, Ill., manufacturers of microphones and electronic components, where he attained the position of Chief Engineer in 1940, and that of Vice President in 1950.

In 1957 he was appointed Head of Audio and Acoustics of the CBS Laboratories. Division of the Columbia Broadcasting System, Inc., Stamford, Conn., and in 1958 he became Vice President of the Laboratories, in charge of the Acoustics, Magnetics, and the Instrumentation Research Departments. During this time, he was responsible for the development of such electroacoustic instruments as microphones, disk recording and reproducing transducers, and magnetic recording devices, and has also been concerned with carrying various products through the research, design, and into the production engineering phase.

Mr. Bauer is a member of Eta Kappa Nu, Tau Beta Pi, ASA, and the Audio Engineering Society. Recently he received the Eta Kappa Nu Award of Merit.

❖

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

Since 1940 he has been a staff member of the Armour Research Foundation, Chicago, where he has been concerned with research in the Electronics Division on such projects as remote control, high-speed photography, magnetostriction oscillators, and static electricity.

M. CAMRAS

He has contributed developments which are used in modern magnetic tape and wire recorders, including high-frequency bias, improved recording heads, wire and tape materials, magnetic sound for motion pictures, multitrack tape machines, and binaural sound reproduction.

Mr. Camras is a member of the Acoustical Society of America, AIEE, SMPTE, AAAS, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He is presently Editor of these TRANSACTIONS, and received the John Scott Medal in 1955 for his work in magnetic recording.

❖

D. F. ELDRIDGE

Donald F. Eldridge (A'50–M'55–SM'60) was born in Passaic, N. J., on January 30, 1929. He received the B.S.E.E. degree from Lehigh University, Bethlehem, Pa., in 1949.

He then joined the Boeing Airplane Company, Seattle, Wash., where he was engaged in work covering many phases of dynamic data acquisition and reduction. In 1956, he became affiliated with the Research Division of Ampex Corporation, Redwood City, Calif., where he did research on many aspects of magnetic recording. His last position there was Head of the Magnetics Department of the Ampex Corporate Research Division, from which he resigned in December, 1960. He is presently Vice President and Technical Director of Memorex Corporation, Santa Clara, Calif.

Mr. Eldridge is a member of AIEE, AIP, SMPTE and AAAS.

❖

S. HIMMELSTEIN

Sydney Himmelstein (S'46–A'48–M'55) was born in New York, N. Y., on October 1, 1927. He received the B.E.E. degree from New York University, New York, in 1947.

Since December, 1960, he has headed the consulting engineering firm of S. Himmelstein and Company, Chicago, Ill., which specializes in magnetic recording systems and computer peripheral equipments. From 1956 to 1960 he was Technical Director of the Data-Stor Division of Cook Electric Company, Morton Grove, Ill., where he was in charge of industrial and military recording systems and peripheral equipment development. He has also been associated with Engineer Research and Development Laboratories, Fort Belvoir, Va., where he handled geophysical research and equipment development, and he worked on the development of radio link telemetry and underwater blast pressure measurement systems while with the Naval Ordnance Laboratory. He has lectured in electrical engineering at the Catholic University of America.

Mr. Himmelstein is a member of the Audio Engineering Society and the National Society of Professional Engineers, and is a Registered Professional Engineer in the State of Illinois.

C. D. Mee

C. Denis Mee (SM'58) was born in Loughborough, England, on December 28, 1927. He received the B.Sc. degree in physics from London University, London, England, in 1948, and the Ph.D. degree from Nottingham University, Nottingham, England, in 1951.

From 1951 to 1954, he was employed by the Magnetics Laboratory of the Steel Company of Wales, where he specialized in research on soft magnetic materials. Then he became associated with the MSS Recording Company, Colnbrook, England, where he was in charge of a research program on the development of data-recording magnetic tape. In 1957 he joined CBS Laboratories, Stamford, Conn., where he is presently Technical Director of the Magnetics Research Department. At CBS he has directed research programs on short wavelength magnetic recording problems, video recording, and new magnetic materials for tape.

Dr. Mee is a member of the Institute of Physics.

C. B. Pear, Jr.

Charles B. Pear, Jr. (A'36–M'55) was born in Gloucester, Mass., on April 10, 1909. He received the B.S. degree in communications engineering from the Massachusetts Institute of Technology, Cambridge, in 1939.

He has been associated with the Industrial Systems Division of the Minneapolis-Honeywell Regulator Co., Beltsville, Md., since 1946, where he specializes in the field of magnetic tape recording and its associated equipment.

Mr. Pear is a member of the Instrument Society of America and the American Meteorological Society.

Irving Stein (M'61) was born in New York, N. Y., on May 28, 1921. He received the B.S. degree in physics from Queens College, New York, N. Y., in 1942; the M.S. degree in physics from Stanford University, Stanford, Calif., in 1949; and the M.A. degree in mathematics from the University of Oregon, Eugene, in 1950. He has completed courses for the Ph.D. degree in physics at Stanford University.

Following military service in 1944, he taught at New York University, New York, at the City College of New York, and at Wayne University, Detroit, Mich. He was then associated with Eaton Manufacturing Co., Detroit, Mich., for four years as a Physicist-Mathematician in the Research and Development Laboratory, where he was concerned with the analysis of engine components, high torque measurements, tension bars, and automated equipment. Currently he is a Senior Physicist in the Research Division of the Ampex Corporation, Redwood City, Calif.

Mr. Stein is a member of the American Physical Society.

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