IRE Transactions on AUDIO

VOLUME AU-3 NOVEMBER-DECEMBER, 1955 NUMBER 6

Published Bi-Monthly

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 assessment of $2.00.

IRE TRANSACTIONS on AUDIO

Published by the Institute of Radio Engineers, Inc., for the Professional Group on Audio at 1 East 79th Street, New York 21, New York. Responsibility for the contents rests upon the authors, and not upon the IRE, the Group, or its members. Individual copies available for sale to IRE-PGA members at $0.95; to IRE members at $1.10; and to nonmembers at $2.85.

Two Grams in 1956?

B. B. BAUER†

AN EVER-POPULAR pastime is that of predicting the future from past events. In 1953, for example, Camras predicted the future speed of magnetic recorders, based upon previous design data. It does not seem unreasonable to apply the same principle to the art of phonograph reproduction.

Fig. 1 is a graph of needle load values in home phonographs during the past three decades. The first point represents the ½-pound weight of the sound chamber and tone arm of many acoustic phonographs during the "gay twenties." Introduction of magnetic pickups late in the decade brought the needle load down to around ¼ pound. In the middle thirties there was a substantial improvement resulting from the early 2 to 3-ounce crystal pickups. Just prior to World War II, "lightweight" 1 to 1½-ounce pickups appeared. The war put a stop to development in the phonograph field, and the pickups which reappeared after the war still were intended for 1-ounce operation. Needle loads dropped to ½–¾ ounce in the latter forties, and were further reduced to 5–7 grams with the introduction of LP records. There has not been a significant improvement since, due, in part at least, to the intervening Korean action.

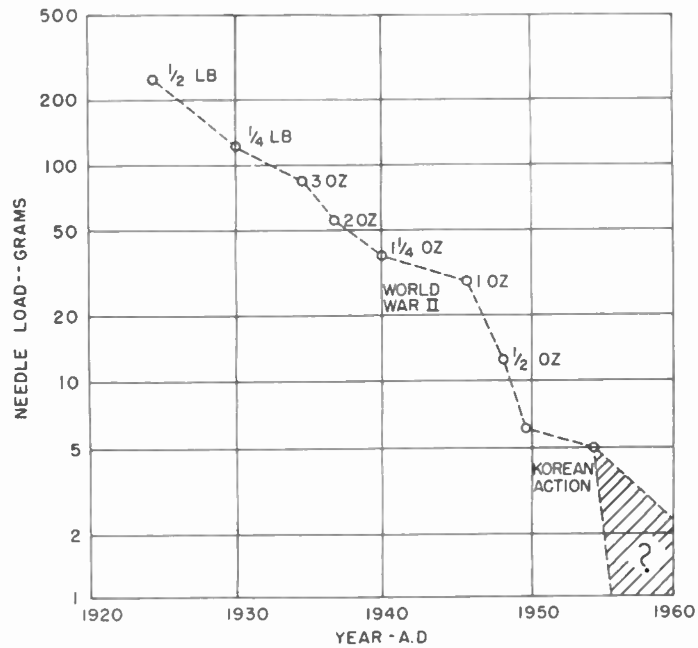


Fig. 1—Progression of needle loads with time.

The graph is a general representation to which many exceptions will be found. Individual experimenters have attempted to lighten the needle load, often with notable success. Pierce and Hunt, for example, described the construction of an electrodynamic pickup in 1938 intended for operation at 2-gram loads, and which they used to confirm their theory of tracing distortion. Without question, the most lightweight pickup is the one described by Williams in 1933 (U. S. Patent 1,917,003) based on the principle of reflection of light from the sidewall of a modulated groove, without an intervening needle-tip. The average pickup in the home, however, has not greatly benefited from these exceptional developments. An investigator armed with a spring scale will soon be convinced that the needle bearing loads in most modern phonographs are nearer 10 than 5 grams.

Anyone believing in prediction by extrapolation will readily see that lower needle loads are soon due to arrive, and should reside somewhere in the shaded area of the graph. This thought may cause apprehension to many a designer of pickups and record changers. A pickup playing, say, at 2 grams, has many difficulties to overcome. There is the problem of securing low enough needle-tip impedance for proper tracking and high enough output for satisfactory electrical operation; the problem of arms of sufficiently low mass to avoid skipping of grooves owing to floor vibrations, and at the same time sufficiently sturdy for ordinary handling. There is a fair-sized design problem of mounting the arm for free and easy motion and reliable actuation of the tripping mechanism in record changers. Two grams, after all, is the weight of a dime worn thin.

What gains may be expected from lowered needle loads? First, significant improvement in the rate of record wear; second, improvement in the quality of reproduction. It is well known that a groove is cut with a sharp edged stylus, but reproduced with a ball-point needle. This geometrical disconformity gives rise to "tracing distortion" first analyzed by Pierce and Hunt, which limits reproduction quality. Lowered needle forces will permit the use of small needle-tip radius with significant improvement in distortion. Smaller tip radius should permit closer groove spacing, thus increasing playback time per record side. A further benefit to be expected is longer needle wear. Previous studies have shown that needle life increases in roughly inverse proportion to needle bearing load, but in a recent paper before the Audio Engineering Society, Dr. Hunt hypothesized that a critical point may exist around 2–3 grams, below which the wear of a sapphire needle would practically disappear. Without claiming comprehensive verification he reports that the sapphire tips in some of his early 2-gram pickups have shown no measurable wear to date. Further, he asserts, surface noise stemming from plastic yielding of the groove is apt to be greatly reduced.

From all indications there are important benefits to be derived from lowering needle loads, and these facts should not escape designers of phonograph equipment.

† Shure Brothers Inc., Chicago 10, Illinois.

PGA Chapter News

STANDARDS ON SOUND AND VIBRATION ANALYZERS

The American Standards Association has recently issued the "American Standard Method for Specifying the Characteristics of Analyzers Used for the Analysis of Sounds and Vibrations," Z24.15-1955.

"This standard is limited to the requirements of analyzers for use in analyzing as a function of frequency a complex electrical signal of relatively long duration, such as that obtained from an electroacoustic or electromechanical transducer."

"The purpose of this standard is to enumerate the important characteristics of such analyzers and to specify the manner in which these characteristics shall be described."

Definitions are given for the following terms: Wave Filter, Band-Pass Filter, Nominal Upper and Lower Cutoff Frequencies, Nominal Pass Band Center Frequency, Nominal Bandwidth, Analyzer, Continuously Adjustable Analyzer, Constant-Bandwidth Analyzer, Constant-Percentage-Bandwidth Analyzer (Proportional-Bandwidth Analyzer), Effective Bandwidth for Random Noise.

Methods of Specifying Characteristics are listed for the following quantities: Frequency Range and Accuracy, Input Voltage Range, Input Impedance, Source Impedance, Output Voltage, Output Impedance, Load Impedance, Power Requirements, Type of Indication, Pass Band Response, Extraneous Influences, Size and Weight, Bandwidth, Transient Response.

NEC AUDIO SESSIONS

At the time copy for this issue was prepared, the NEC was still several weeks off. A fine session of this conference was sponsored by the IRE Professional Group on Audio and we assume that it came off with flying colors. We should all make a strong effort to sponsor an additional session on Audio next year.

SHURE ACOUSTICS SCHOLARSHIPS

A scholarship of $800 has been established at Illinois Institute of Technology and another one of $800 at Northwestern University for a senior or graduate student specializing in acoustics.

The scholarships, which cover tuition costs for a year, were created by Shure Brothers, Inc., Chicago manufacturers of microphones and acoustic devices. Known as the Shure Acoustics Scholarships, the grants will be on the basis of scholarship, need, and interest in electroacoustics.

Further information may be obtained by contacting Dr. William A. Lewis, dean of the I.I.T. graduate school or Dean, Technological Institute, Northwestern University, Evanston, Illinois.

WITH OTHER ACOUSTICAL AND AUDIO SOCIETIES

The July, 1955 issue of the *Journal of the Acoustical Society of America* contains 24 papers on Acoustics and Audio. Five of these will be of special interest to the members of the IRE Professional Group on Audio.

"On Webster's Horn Equation," E. S. Weibel, p. 726. A wave equation for the sound propagation through tubes is derived by means of Hamilton's variational principle. It is assumed that the wavefronts can be approximated by surfaces of constant stream potential; this is the only assumption made. The variational principle ensures that the best equation that is compatible with this assumption will be obtained. The equation has the form of Webster's horn equation; however, its coefficients are defined differently.

"Some Development in Vibration Measurement," S. Edelman, E. Jones, and E. Smith; p. 728. This paper describes cemented barium titanate accelerometers of two simple types, an electromagnetic shaker with a symmetrically mounted shake table, a set of barium titanate shakers, and two optical methods of accelerometer calibration, one using a microscope with a stroboscope of wide frequency range and one using a Fizeau type interferometer. Calibration results from 50–11,000 cps are given.

"Comparison of Objective and Subjective Observations on Music Rooms," J. Blankenship, R. B. Fitzgerald, and R. N. Lane; p. 774. A comparison of the physical and acoustic measurements in several music rooms at the University of Texas with the subjective reactions of the musicians working in these spaces. Emphasis is placed on the musicians' viewpoint in regard to desirable room characteristics.

"Touch Sensitive Organ Based on an Electrostatic Coupling Device," H. Le Caine; p. 781. A device for coupling generators to sound systems in electric musical instruments is described, particularly in connection with its use in a touch-sensitive keyboard. The construction of such a keyboard is shown to be quite straightforward. Many well-known types of generators and any timbre control system may be used. The musical value of a touch-sensitive action is difficult to assess, but the writer is impressed favorably.

"Articulation Scores for Two Similar, Reverberant Rooms, One with Polycylindrical Diffusers on Walls and Ceiling," L. A. Jeffress, R. N. Lane, and F. Seay; p. 787. Two rooms of about the same dimensions, one a rectangular parallelopiped, and one having polycylindrical walls and ceiling, were parallelopiped, and one having polycylindrical walls and ceiling, were measured for reverberation times and for speech articulation. No significant differences were found in either characteristic. Since one of the rooms should provide a more diffuse sound field than the other, it can be tentatively concluded that diffusion may have little influence on speech intelligibility. Both rooms exhibited rather poor articulation scores as might have been predicted from their reverberation times.

Mr. R. C. Mathes has written a Letter to the Editor on the subject of Monaural Direction Finding.

The July, 1955 issue of the *JASA* contains the customary excellent section on references to contemporary papers on Acoustics and Review of Acoustical Patents.

The January, 1955, issue of the *Journal of the Audio Engineering Society* contains six excellent papers, all of which might be of interest to IRE-PGA members. They are as follows:

"On Stylus Wear and Surface Noice in Phonograph Playback Systems," F. V. Hunt, p. 2. A theory of rubbing wear found useful in other fields predicts that the volume of stylus (or record) material worn away is proportional to the area of "real" contact between the stylus and the groove wall. In order to evaluate the influence of system parameters on the real-contact area, the elastic plastic regime prevailing under the stylus is first analyzed in detail. The enhancement of the effective yield strength of record materials by the so-called size effect is found to have a dominant influence on the stylus-groove contact. Application of these results to the wear problem leads to the prediction that stylus life could be extended by as much as one or two orders of magnitude if the conventional dynamic loading of the stylus contact were lowered enough to insure that no plastic yielding could ever occur even at the peak acceleration demand for either vertical or lateral motion. Avoidance of plastic yielding is also shown to remove an important component of surface noise originating in the microscale intermittency of plastic flow.

"Record Quality and Its Relation to Manufacturing," A. M. Max, p. 19. Describes the various operations in the manufacturing of records and their relation to record quality.

"Frequency-Modulation Noise in Magnetic Recording," R. A. von Behren and R. J. Youngquist, p. 26. Certain noise effects associated with high-frequency recorded signals are attributable to rapid fluctuations in the speed of the magnetic tape as it passes over the recording heads. The high-frequency tape flutter may be caused by resonant longitudinal vibrations which are excited by random frictional forces. The flutter rate can be determined theoretically from a consideration of the mechanical properties of magnetic tape, and the calculations verified by actual measurement with a frequency discriminator and spectrum analyzer.

"Defects in Magnetic Recording Tape: Their Cause and Cure," F. Radocy, p. 31. The presence of imperfections in the surface of magnetic tapes has been a problem in the computer, telemetering, and home recording fields. Tape squeal, sticking, and level variations have been caused by deposits on the head due to the shearing of imperfections in the oxide. Because of the effect of level variation in the computer field, the latter phenomenon has generally been referred to as "dropout." Through improved binder formulation and coating techniques, a precision tape has been developed in which coating imperfections are virtually eliminated as a source of dropouts.

"Correlation of Transient Measurements on Loudspeakers with Listening Tests," M. S. Corrington, p. 35. The transient distortion of a loudspeaker may be measured by intermittently applying sine-wave bursts, consisting of 4 or 16 cycles each, to the speaker. Each burst starts with the wave going through 0° and ceases, after the desired number of cycles has been counted off, with the wave once again crossing the zero axis. Each burst is followed by an "off" period whose duration is equal to that of the burst; the burst is then repeated. A microphone situated in front of the loudspeaker is gated to measure the sound "hangover" during the "off" period. A curve is then drawn of this transient hangover as a function of frequency. The correlation of the curve thus obtained with listening tests is discussed.

"Multi-impedance, Multifrequency Crossover Networks for Multispeaker Systems," A. B. Cohen, p. 40. A unitized network system is described which makes possible a wide choice of crossover points and attenuation rates, matched to a wide range of speaker impedances for the purpose of achieving the most compatible performance from the speakers chosen for a multi-speaker system.

B. B. Bauer

PGA CHAPTER ACTIVITIES

Boston, Massachusetts

Officers for the Boston Chapter for 1955–56 Season:

Mr. Weiant Wathen-Dunn, *Chairman*
Airforce Cambridge Research Center
Bedford, Mass.

Mr. John S. Boyers, *Vice-Chairman*
National Company
Malden, Mass.

Mr. Henry S. Littleboy, *Secretary*
Hycon-Eastern, Inc.
Cambridge, Mass.

John A. Kessler, Acoustic Lab., M.I.T., announced the election of the above officers, also the joint meeting of the Chapter with the Section, scheduled for October 20, 1955 in the new Kresge Auditorium at M.I.T. The subject of the meeting was "Acoustical Design of the Kresge Auditorium." Speakers were Richard H. Bolt, Professor of Acoustics in the Department of Electrical Engineering, Director of the M.I.T. Acoustic Laboratory, and Consultant in Acoustics with Bolt-Beranek-Newman, Inc.; Robert B. Newman, Assistant Professor of Architecture at M.I.T., and Consultant in Acoustics; and Gabriel Farrell, Jr., Member of the Research Staff at the M.I.T. Acoustics Laboratory.

Résumé of the Acoustical Design of the Kresge Auditorium

The Kresge Auditorium and Chapel were conceived as a cultural and religious center for the M.I.T. community, designed by Eero Saarinen and Associates, endowed by the Kresge Foundation. The Auditorium building contains a 1,200-seat main auditorium, a 200-seat theatre, rehearsal rooms, storage, and operating facilities. It can accomodate a wide range of program material, from speech to organ music; all rooms may be used simultaneously without interference from high sound levels in adjacent rooms; the novel dome structure and the unconventional form posed unusual problems in acoustical designing, all of which were overcome; in some instances a number of double "sandwich" constructions were devised for noise isolation, and treatment of the air-conditioning ducts was designed to reduce mechanical noise and to prevent transmission of sound between spaces.

Upholstered seating has been installed to provide needed reverberation control, special sound-absorbing treatment was designed to control echo from the curved rear wall, a number of free-hanging reflecting panels have been placed over the stage and seating area to obtain good distribution of sound throughout the seating area—these panels also provide mixing or blending for musical performances and serve to screen ducts, loudspeakers, lighting fixtures, etc. Measurements of the acoustical characteristics were made during construction and provided a basis for final adjustments to the acoustical treatment.

The Audio System permits sound reproduction in the main auditorium, theatre, and rehearsal rooms from live programs, disc and tape recordings, sound pictures or programs received from remote points by radio or telephone. Provision is also made to pick up programs in the several rooms for recording or transmission; and independent system for speech reinforcement in the main auditorium is available for use when desired.

Following the speakers, there was a demonstration and a discussion period, after which the Auditorium and Chapel were formally opened for inspection.

The new Chapter officers feel that they have two big problems in programming their meetings for the Boston Chapter of the IRE-PGA. First, securing good technical papers and stimulating some new work in the field. Second, presenting a varied enough program so that each member feels that, during the year, there is at least one program particularly suited to his wishes and needs.

Besides the October meeting which was of interest to a great many people, both in and out of the PGA Chapter, interesting sessions have been planned for December, February, and April.

Cleveland, Ohio

Cleveland's flourishing Chapter is in capable hands for the coming year. One of the first steps taken by the new officers was the Questionnaire mailed to all Section news readers. They feel that the effort and expense connected with this poll will be well worthwhile in securing exact areas of interest from the members, in order to set up the programs to please the majority.

Thumb-Nail Biography of Cleveland's New Officers

Ed Wagenhals: Director of Components Development at the Clevite Research Center. Born in Muncie, Indiana, educated at Denison; started his career at the General Electric Co., went on to Cleveland Vacuum Tube Works; then became Senior Engineer at RCA, later was Chief Engineer and Manager of Manufacturing and Engineering for the L. E. Waterman Company; Production Manager at Sonotone Corporation; Associate in the consulting firm of Booz-Hamilton-Allen until early in 1955, when he joined Clevite-Brush as Vice-President.

Carmen Germono: Vice-Chairman of IRE-PGA. B.S.E.E. from Northwestern, M.S. in Physics from John Carroll. Formerly with Victoreen Instruments. Has been with The Brush Corp. since 1950, head of Crystal Measurements Group. Mr. Germono is an energetic engineer with great interest in the advancement of the IRE, particularly the Audio group; therefore the programs for 1955–56 should include outstanding audio personalities and authorities.

Jack Goldfarb: Secretary IRE-PGA. An institution in Cleveland electronic circles, Mr. Goldfarb has been with REPCO since 1939. A ham of long standing, known to all hams in the area, as well as to all pros and semi-pros who ever burned their fingers on a vacuum tube. Attended Fenn College. Instructor with Signal Corps stationed in Europe during World War II. Great Hi-Fi enthusiast. Faithful in attendance to all PGA Sessions.

Cleveland's City Council Majority Leader Jack Russell is a great booster for Hi-Fi. He has an outstanding example of a stereophonic installation in his home. In fact, it is a dream set, and the Cleveland Chapter promises a complete description in their next News résumé.

Correction: Mr. Kenneth R. Hamann of station WDOK, AM and FM, points out that a statement regarding the AFTRA award, appearing in the July-August, 1955, issue under Cleveland PGA Chapter activities is in error. He states that the AFTRA award was presented solely to station WDOK at the spring awards presentation.

Syracuse, New York

The first meeting of the Syracuse Chapter for the 1955–56 season was held October 6th. Dr. W. E. Kock, Director of Acoustic Research for the Bell Laboratories and present National Chairman of the IRE-PGA, was the guest speaker. His subject was "Speech, Music and Hearing." The physical concepts underlying the speech process and hearing process were outlined. Demonstrations of synthetically produced speech sounds and musical tones were given, as well as examples of speech and recreated synthetically from actual speech and music.

In June a questionnaire was mailed both to Syracuse Section PGA members and to others who had at one time evidenced interest in Syracuse PGA activities. The chief purpose of the questionnaire was to determine the types of programs and areas of greatest interest to the local group. It was felt that this would be of great help in planning meetings for the 1955–56 season. Replies were received from 40 per cent of those canvassed. Some of the information gained may be of general interest to other PGA Chapters and is given below:

Subjects in which Most Were Interested	1st choice	2nd choice	3rd choice
1. High Fidelity Home Music Systems	12	3	1
2. Magnetic Tape Recording	4	5	1
3. Loudspeakers	0	1	7
4. Audio Amplifiers	0	3	4
5. Subjective Aspects of Audio System Evaluation	2	1	3

There was scattered but somewhat lesser interest in the following:

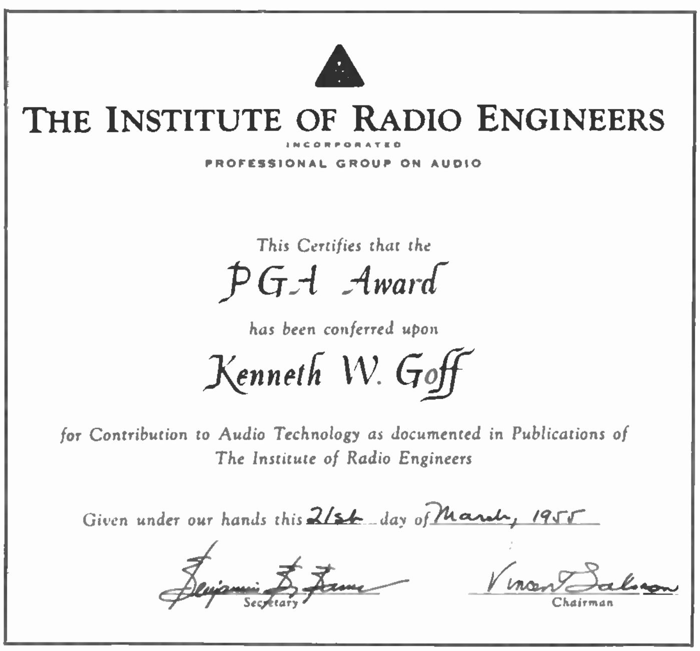
1. Binaural and Stereophonic Sound Technique
2. Audio Design
3. Photograph Pick-ups and Arms
4. Audio Measurements
5. Acoustics—Auditorium and Listening Room

In addition, it was learned that the majority of those who returned the questionnaire would like—and would be willing to pay for—a lecture series on some phase of audio engineering. The particular phases in which interest was expressed was almost as diverse as the tabulation above.

In evaluating the results of the questionnaire it is pertinent to note that Syracuse (a city of approximately 230,000) has relatively few engineers engaged professionally in the field of audio engineering. The major interest among engineers in audio is avocational; so the indicated predominance of interest in high fidelity systems and components is not surprising.

PGA AWARD CERTIFICATES

The certificates below were presented to Mr. B. B. Bauer and to Mr. Kenneth Goff as described under PGA Award Recipients in the July–August 1955 issue of the IRE Transactions on Audio. The original parchment certificates bear the gold IRE seal. These certificates are symbols of achievement for which every member of the PGA should strive.


THE INSTITUTE OF RADIO ENGINEERS
INCORPORATED
PROFESSIONAL GROUP ON AUDIO

This Certifies that the
PGA Award
has been conferred upon
Kenneth W. Goff

for Contribution to Audio Technology as documented in Publications of The Institute of Radio Engineers

Given under our hands this 21st day of March, 1955

Secretary   Chairman


THE INSTITUTE OF RADIO ENGINEERS
INCORPORATED
PROFESSIONAL GROUP ON AUDIO

This Certifies that the
PGA Achievement Award
has been conferred upon
Benjamin B. Bauer

for Contribution to Audio Technology as documented in Publications of The Institute of Radio Engineers

Given under our hands this 21st day of March, 1955

Vice Chairman   Chairman

Tape Recording Applications*

MARVIN CAMRAS†

Summary—**Standard designs are flexible enough for most uses of tape recorders. Special machines have been devised for unusual applications such as pronouncing dictionaries, length measuring devices, time compressors, dc and square wave recorders, memory devices, and automatic machine control. The construction and operation of typical devices are reviewed.**

EVEN to list all the applications of magnetic recording would require more room than this entire paper. However, we can discuss a few interesting uses that are typical, but which may not be well-known except to specialists in the field.

Data Handling and Computers

There is much ado, lately, about magnetic memories for computers. Why do they need a memory and what kind is ideal? We can understand better if we set up and run through a simple problem.

Everyone should know how to operate an electronic computer. Who knows?—as life becomes more complicated you may decide to buy one. Suppose that you bring it home with you and test it on your daughter's algebra problem which is to evaluate a function:

$$x^2 + axy + by^2$$

for a series of x's and y's.

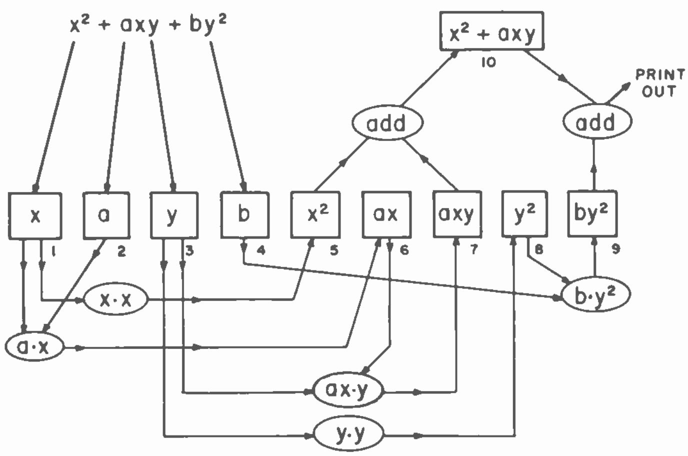


Fig. 1—Operation of a computer in solving an elementary problem.

First you must store numerical values of x, y, a, and b somewhere. According to Fig. 1, convenient storage registers 1, 2, 3, 4, etc., are provided for this purpose. You then operate by instructing the machine to take the x-value from storage 1, multiply it by itself, and store the result (x^2) in 5. Next you "tell" it to take the x-value from storage 1, the a-value from storage 2, multiply them together and place the result (ax) in 6. To get axy, the number in 6 is multiplied by the number in 3, and addressed to 7. Similarly you find and store by^2. Registers 5, 7, and 9 now contain the terms you want. You proceed by adding the values in 5 and 7, storing them in 10. Finally you add the results of 9 and 10, which is the answer, so you instruct the machine to print it out.

The operations take only a few microseconds, after which you tear off the printed slip, and your daughter hands it to her teacher.

You've used ten storage spaces, which is wasteful. When you are more experienced or read the instruction book, you'll find that after the second step you didn't need x any further, so you could have cleared storage 1, and put the result there, instead of in 6.

The memories we described are simple; they hold only a single number. But they must act fast and must be available instantly. We can't wait for tape to roll around, so we use flip-flop tubes, mercury or quartz tanks, cathode ray electrostatic memories, or magnetic core memories.

We notice a severe bottleneck at the output of the machine. No mechanical printer is fast enough to print the results. Here we can use a magnetic tape. With the results on tape we can print at leisure, and release the computer. Or sometimes the results are an intermediate step that we don't print. We save them on tape, for running through the machine again later.

Another bottleneck is the input. We don't have to tie up the computer while setting up a program, but can put it on tape first, and when ready, feed the tape to the computer. We soon build up and save a tape library of computer programs. Once a week we play the payroll tape, and come out with a bundle of checks. Inventory in a large mail-order house might be revised daily. In between times we may compute guided missile paths.

Fig. 2 shows a tape recorder designed for computers, and is typical of the many kinds that use reels of tape.

Fig. 3 (page 176) is an experimental memory which uses an endless loop of tape.

One of the latest systems (the NORC) stores 500 characters per inch at a speed of 140 inches per second, to give 70,000 decimal digits per second.

Note the contrast between the built-in machine memory, and the tape memory. The built-in memory is fast

* Manuscript received September 6, 1955. Paper delivered at the New York IRE Convention, March 22, 1955.
† Armour Research Foundation of Illinois Institute of Technology, Chicago, Ill.

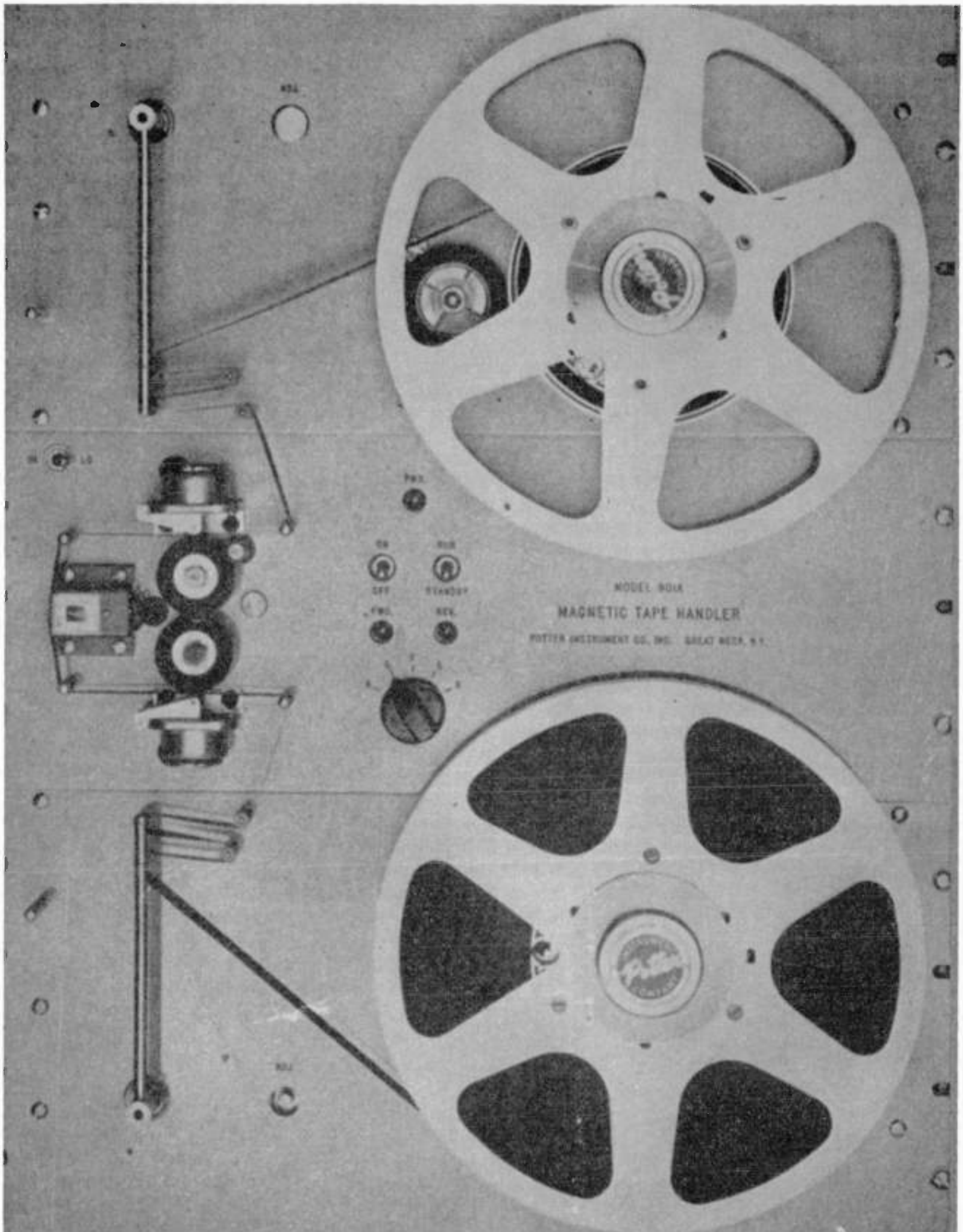


Fig. 2—Potter 902 digital tape handler. Number of channels—2 to 8; maximum speed—60 inches per second; start and stop time—5 milliseconds; tape—$\frac{1}{4}$ to $\frac{3}{4}$ inches wide; capacity—1,200 to 2,400 feet maximum. (Potter Instrument Co., Great Neck, N. Y.)

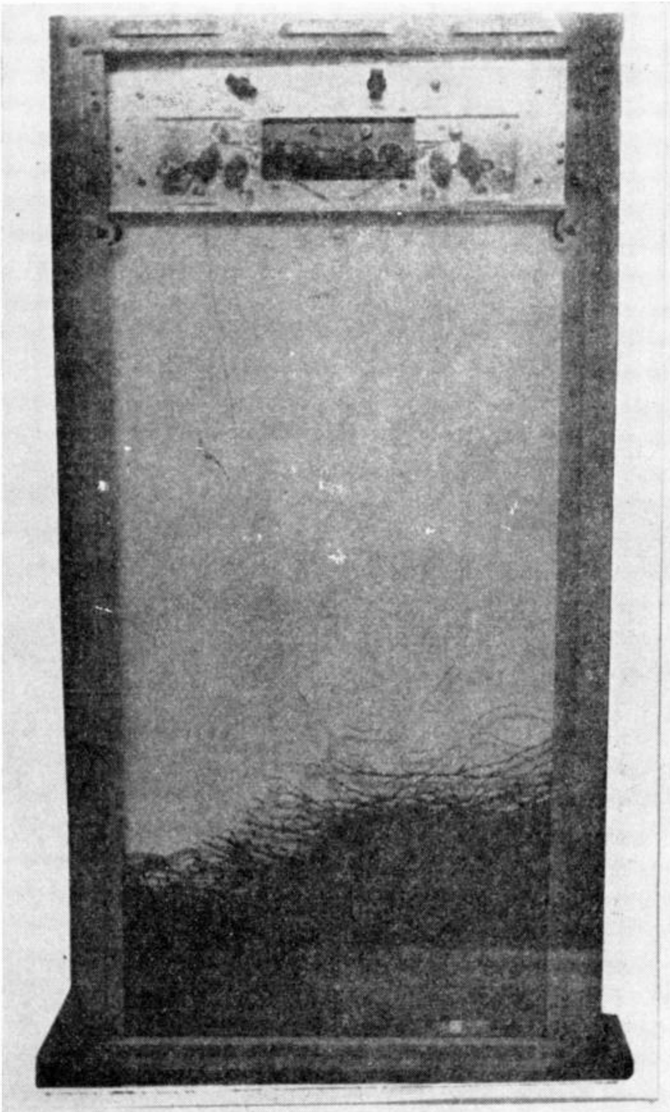


Fig. 3—Memory for SEAC (an early Bureau of Standards) computer held 1,200 feet of ¼-inch tape in a glass front reservoir. A radioactive discharger was necessary to cure trouble with static charges. (*NBS Tech. News Bull.*)

and instantly accessible, but its capacity is very limited, and in most cases not permanent. On the other hand, a tape memory has tremendous capacity, is quite permanent, but has poor accessibility.

In complex problems there is need for an intermediate memory, with more capacity than the built-in memory, and better accessibility than a reel of tape. One answer is a high-speed magnetic drum with multiple heads on its periphery. Fig. 4 is a 20,000 digit drum memory where the maximum access time is only 2.5 milliseconds—achieved by a small diameter driven at 23,500 rpm. Other drums have been made with 200 heads and 400,000 digit capacity.

Figs. 5 to 13, mostly self-explanatory, show how magnetic recording is used in a typical commercial computer. A computer of this kind costs about a quarter of a million dollars a year for equipment rental alone; but they are so handy to have around that the demand exceeds the supply.

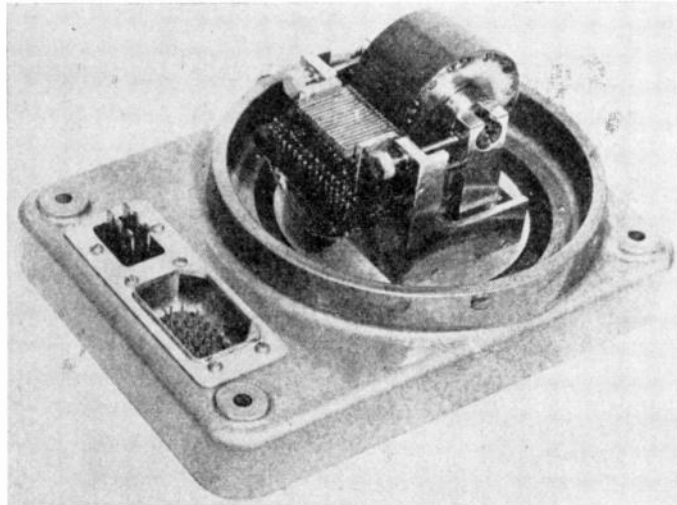


Fig. 4—Ferranti Type 200B Magnetic Drum. Material—2-inch diameter brass, oxide-coated; speed—23,500 rpm driven by 3-phase 400-cycle field; access time—2.5 milliseconds; number of tracks—20; capacity—20,000 binary digits total. (Ferranti Electric Inc., New York, N. Y.)

A more specialized use for the drum memory is the stock quotation machine of Fig. 14 (page 178). In Toronto, a broker dials the code number of a stock, and receives bid and asked prices on his ticker tape or printer. A similar drum is used for reservations in American Airlines. Others have been designed for inventory control in several American companies.

An unusual recorder is shown in Fig. 15 (page 178). Rotating heads scan stationary tape wrapped part way around a drum. The scanned portion, called a page, contains up to 250,000 digits. Fig. 16 (page 179) shows how an advancing mechanism moves the tape to a new page. As a memory system this unit combines advantages of both tape and drum recorders.

For those who prefer something larger the drum of Fig. 17 (page 179) holds 100,000 words. The first model was three feet in diameter.

Business Machines

Now let's look at some office and business machines. Fig. 18 (page 179) fulfills Poulsen's dream when he made the first magnetic recorder in 1898. He wanted it to answer a telephone when no one was in the office. This machine not only answers the telephone, but takes up to 20 messages, which it repeats to the owner on his return.

The most recent dictation machines use magnetic belts or flat sheets. In Fig. 19 (page 179) the record is in belt form, and slips over an expanding drum. It features quick accessibility to any part of the record, long recording time, and mailability. Another type shown in Fig. 20 (page 179), has a belt that runs over a pair of drums, while the model of Fig. 21 (page 180), has a flat, letter size sheet that wraps around a roller.

For very long recordings we can use a side-scan recorder of Fig. 22 (page 180), taking up to 48 hours on a 7-inch diameter reel of 3-inch wide paper tape. Four heads are mounted on a disc, and record a series of arc-

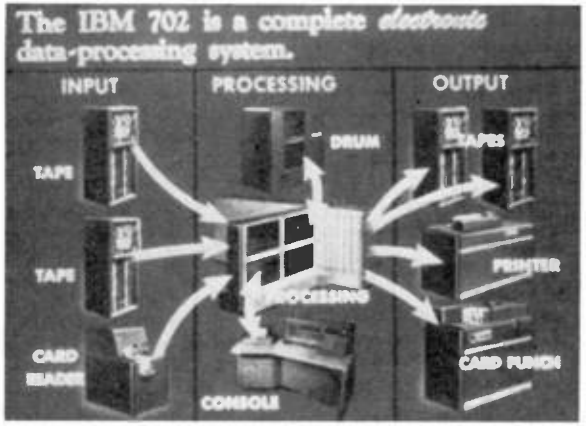


Fig. 5

Fig. 6

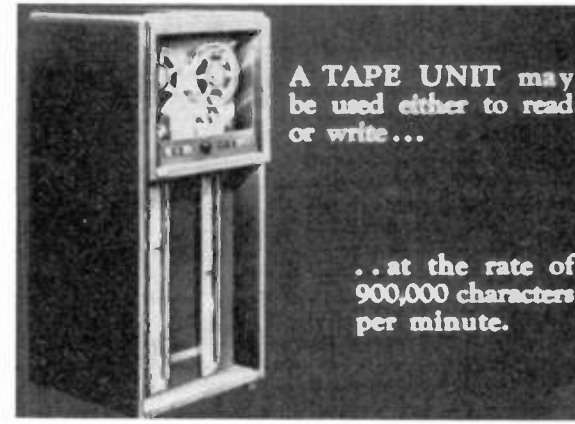


Fig. 7

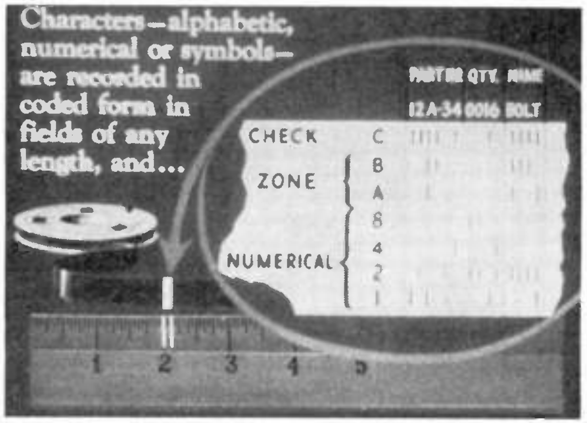


Fig. 8

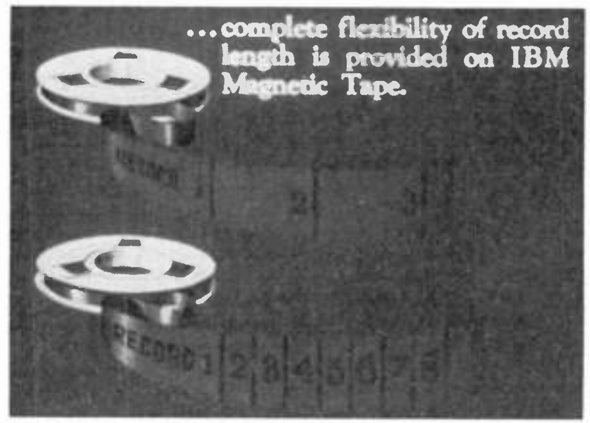


Fig. 9

Fig. 10

Fig. 11

Fig. 12

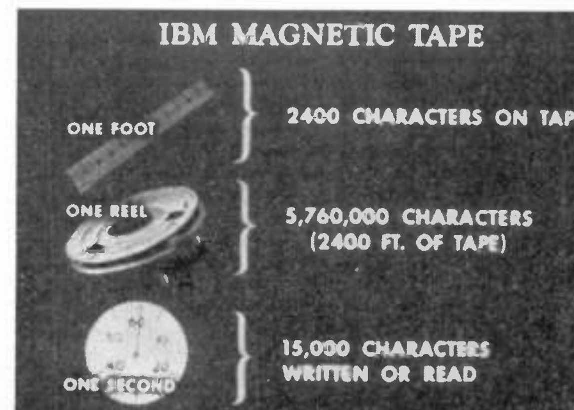


Fig. 13

Figs. 5 to 13—The IBM Model 702 electronic data-processing machine.

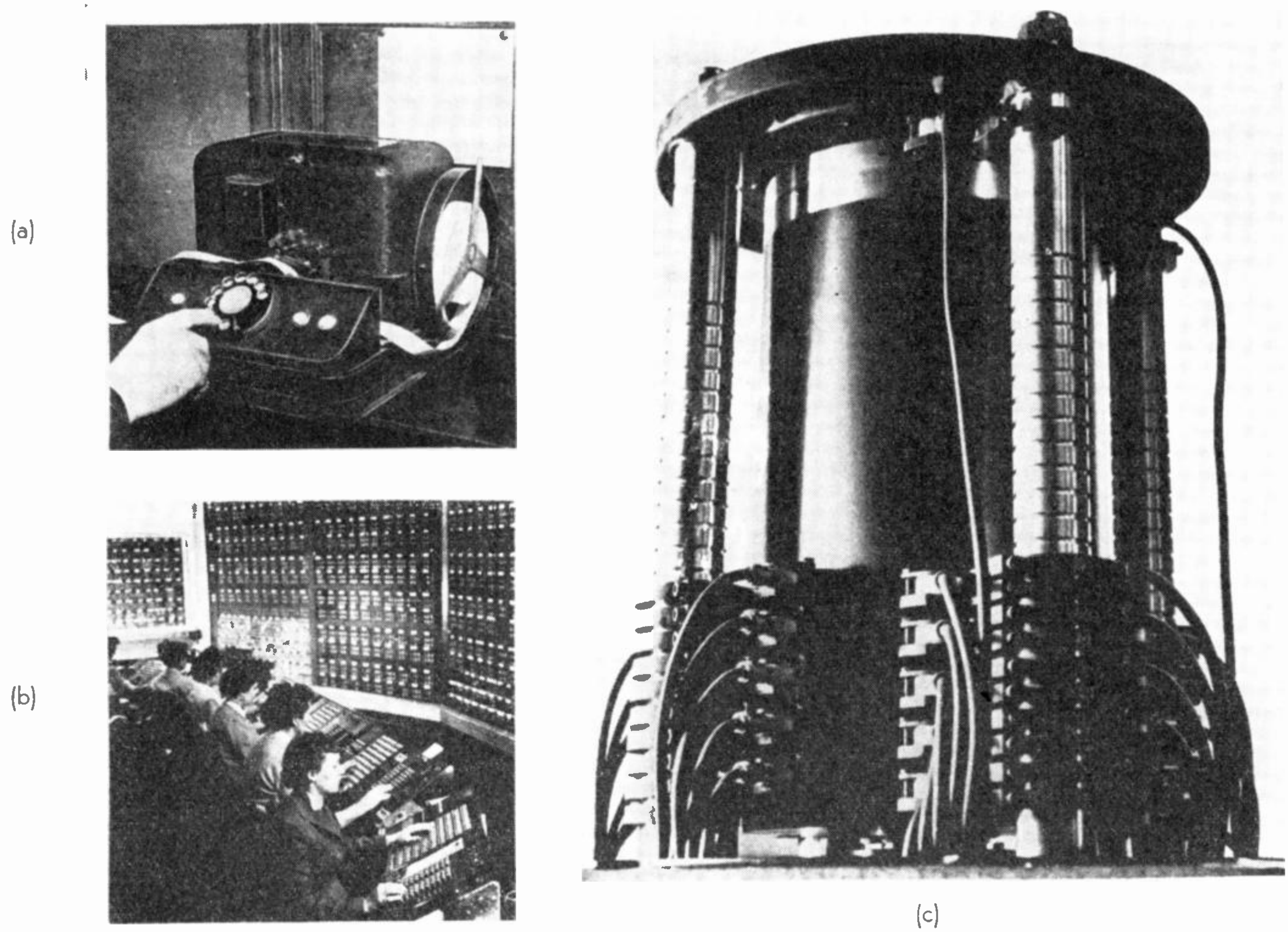


Fig. 14—Stock quotations from magnetic memory are a regular service of the Toronto, Canada, Stock Exchange (*Automatic Control*). (a) Broker's office uses dial-operated transmitter to request quotation, receives bid-ask prices on tape printer. (b) Stock quotations from Exchange floor are posted on quote board and magnetic drum by these operators. (c) Magnetic drum supplies stock quotations automatically from storage in response to dial ticker requests from brokers.

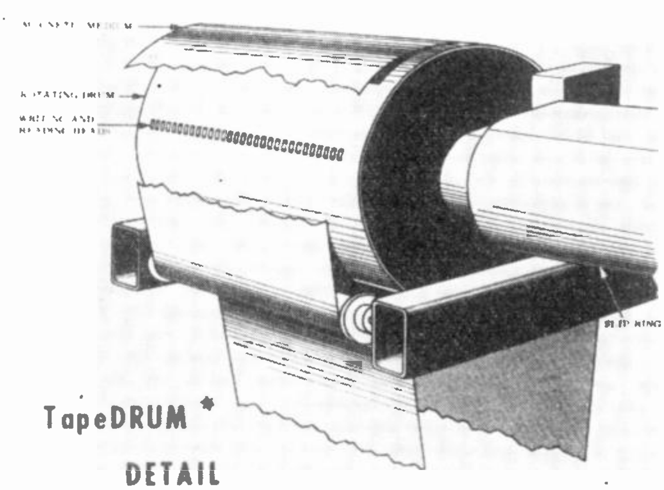


Fig. 15—The tapedrum uses 128 heads on a rotating drum 12 inches in diameter and 14 inches wide for repeated scanning of a page of information. (Brush Electronics Co.) * Trademark.

shaped tracks across tape. Linear tape speed: $9\frac{1}{4}$ inch/minute.

At the other end of the scale is the message repeater of Fig. 23 (page 180). It is about billiard ball size and has an endless loop of tape in a $2\frac{1}{2}$-inch cartridge. It repeats messages a few seconds to three minutes long, for advertising displays, etc. It is interesting that a cartridge of about this size is available to fit on ordinary tape recorders, and may be used for pre-recorded selections.

Scientific and Industrial

One phase of automation, or the automatic factory, is shown in Fig. 24 (page 180). Here a tape record controls a contour shaping machine. A quick way of setting up is to have a skilled workman turn out a part. His motions of the controls are recorded, and the tape will afterwards turn out similar parts at higher speed. Or the tape can be set up from drawings, and will perform simultaneous movements impossible for a human operator.

Many instrument applications require recording and playback down to dc. The magnetic modulator head of Fig. 25 (page 180) is sensitive to flux at tape speeds down to zero. It works on the principle of a magnetic amplifier controlled by the tape flux. Fig. 26 (page 181) shows shows how this head was used to measure the cooling curve of a thick metal bar quenched from high temperature. The commutator was connected to about ten thermocouples located throughout the bar. Additional seg-

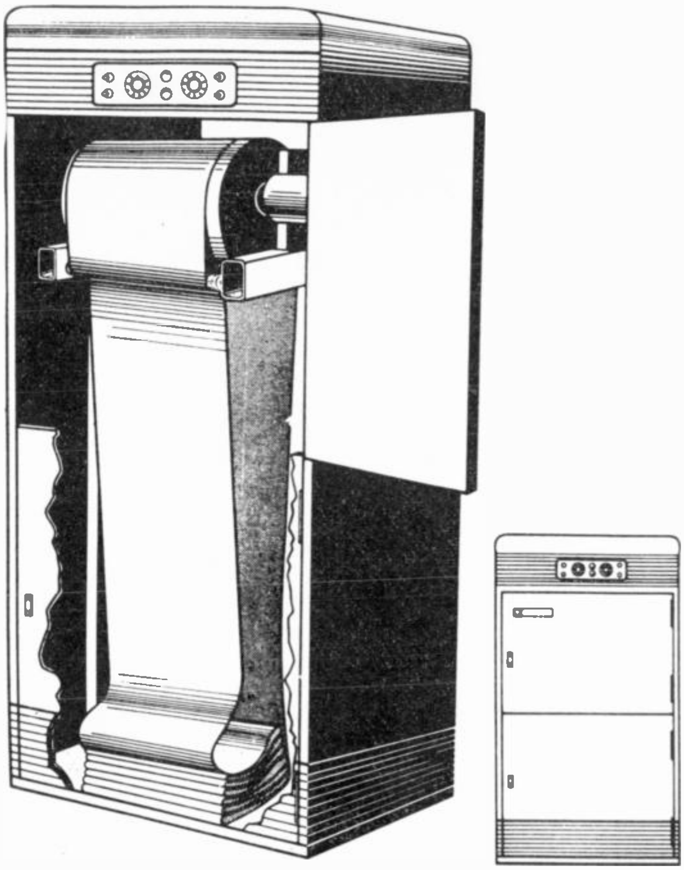


Fig. 16—A complete tapedrum unit incorporates page advancing and selection mechanism. (Brush Electronics Co.)

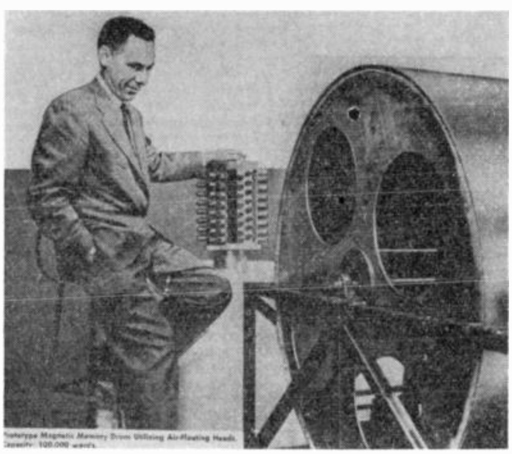


Fig. 17—Large magnetic memory drum. (From *Computers and Automation.*)

ments supplied three levels of standardized voltage for reference, and a negative pulse that signified the beginning of each set of readings. Rotating at high speed the commutator recorded hundreds of readings in the few seconds during quenching. The tape was then played back at about 2 inch/minute with a modulator head. At this slow speed information was transferred to a pen and ink recorder for analysis.

Magnetic recording can measure the length of steel wire, sheet, or other magnetic material while passing through a mill at variable and unknown speed. A record head and playback head are set on the steel exactly one foot apart in the direction of travel. To start counting,

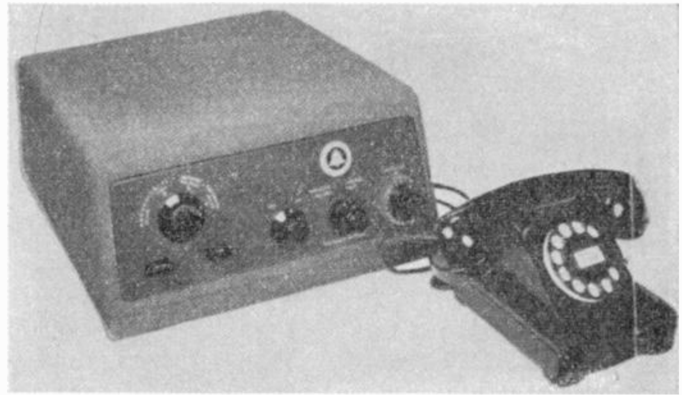


Fig. 18—Telephone answering machine takes up to twenty messages of 30 seconds each, plays them back to the owner when he returns. (The Bell System.)

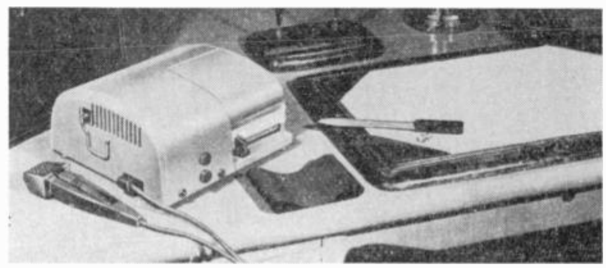


Fig. 19—Drum dictation machine with removable belt. (Pierce Dictation Systems, Chicago, Ill.)

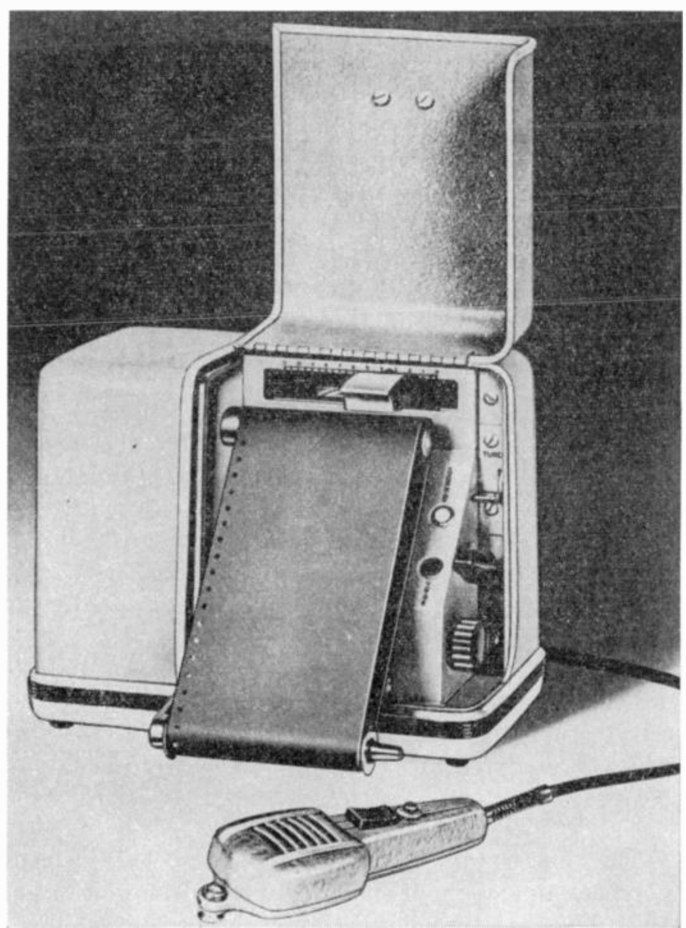


Fig. 20—Belt dictation machine. (Felt and Tarrant Mfg. Co., Chicago, Ill.)

Fig. 21—Flat-sheet dictation machine. (ACEC, Belgium.)

Fig. 22—A side-scanning recorder that can record 48 hours on a 3-inch wide tape. (Soundscriber Corp., New Haven, Conn.)

Fig. 23—Compact message repeater. (Mohawk Business Machines, Brooklyn, N. Y.)

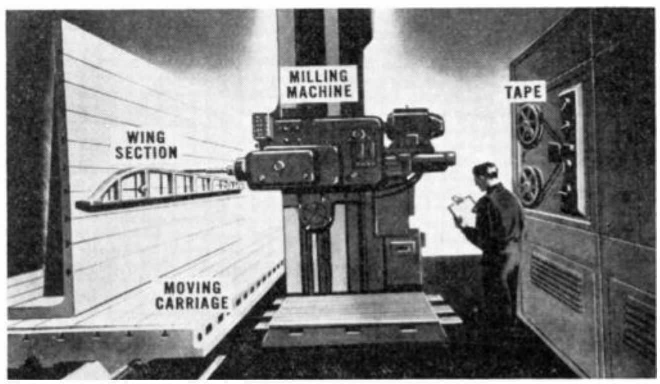


Fig. 24—Automatic programming of machinery. (General Electric Co., Schenectady, N. Y.)

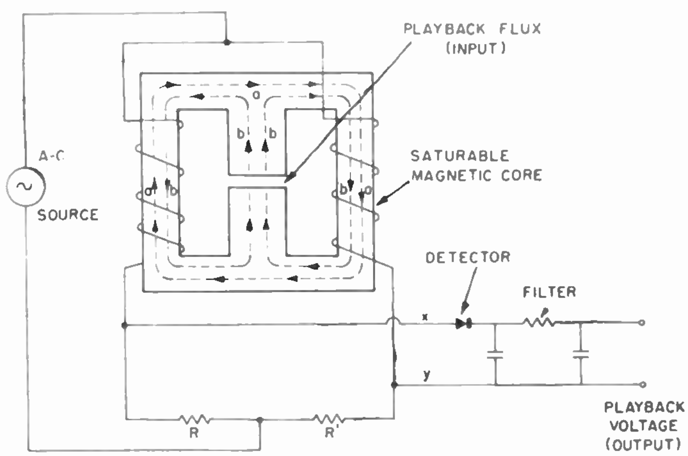


Fig. 25—Principle of the magnetic modulator playback head. (Armour Research Foundation.)

a pulse is recorded on the steel by the recording head. One foot later the pulse is picked up by the playback head which feeds back to the record head, and puts another pulse one foot behind. A counter records the number of pulses and number of feet.

Fig. 27 is an accelerometer that records transient accelerations between 10g and 350g. It is loaded with seven seconds of tape, pre-recorded with a 1,270-cycle carrier. The spring driving motor is started by melting an electric fuse wire. A permanent magnet mounted on the seismic element, partially erases the carrier in accordance with the acceleration. The final record is wrapped on a drum surface, and played repeatedly for oscillograph analysis.

Fig. 28 shows the use of a recorder for later analysis of "one shot" data in exploring for oil. The wide band record can later furnish various kinds of oscillograms which formerly required additional "shots."

Entertainment and General Purpose

The time compressor of Fig. 29 (page 182) reduces playback time without changing pitch. Compressions of 10 to 20 per cent are hardly noticeable, and even 50 per cent is quite intelligible. Its principle of operation is that human speech is so redundant that we can cut out 90 per cent of a word at very small intervals and make sense out of what is left. An analogy is the sign on a board fence in Fig. 29. We remove every other board and put the rest together. The compressed sign is still readable.

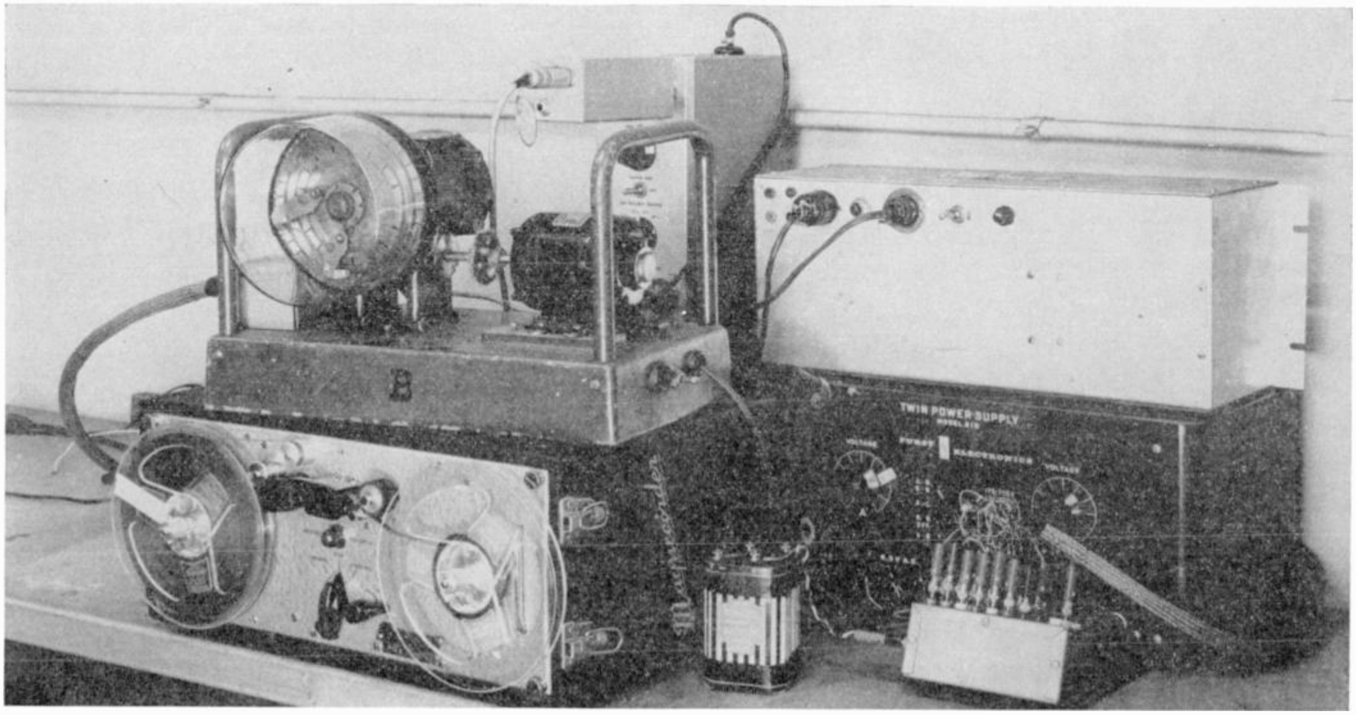


Fig. 26—Multiplex high-speed temperature recorder. (Armour Research Foundation.)

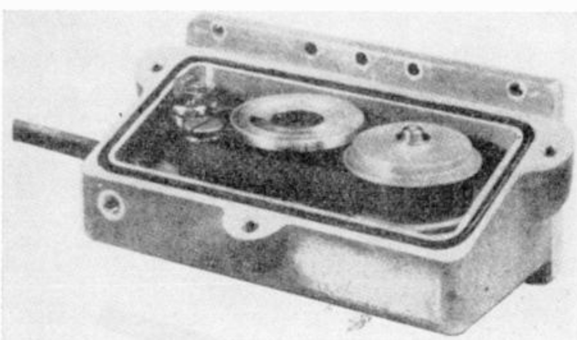


Fig. 27—Structural accelerometer—open. (Engineering Research Associates, St. Paul, Minn.)

A rotary head at *B* chops an audio signal the same way, allowing political speeches to be cut 25 per cent and still say the same thing.

Fig. 30 is a commercial pocket size record-playback machine that picks up sound from a considerable distance. It is magazine-loading, and runs on self contained batteries that last 45 hours or longer. Suggested uses are "voice snapshots," detective work, and a general purpose "notebook" for reporters, salesmen, and students.

Fig. 31 is a two-minute disc recorder designed as a toy for children.

Fig. 32 is an eight mm projector with a magnetic sound track. It is the economical "small brother" of the sixteen mm units that are widely used in professional work. This eight mm projector and striping service are commercially available.

Educational

A very different machine from the usual recorder is the talking dictionary called the "Language Master,"

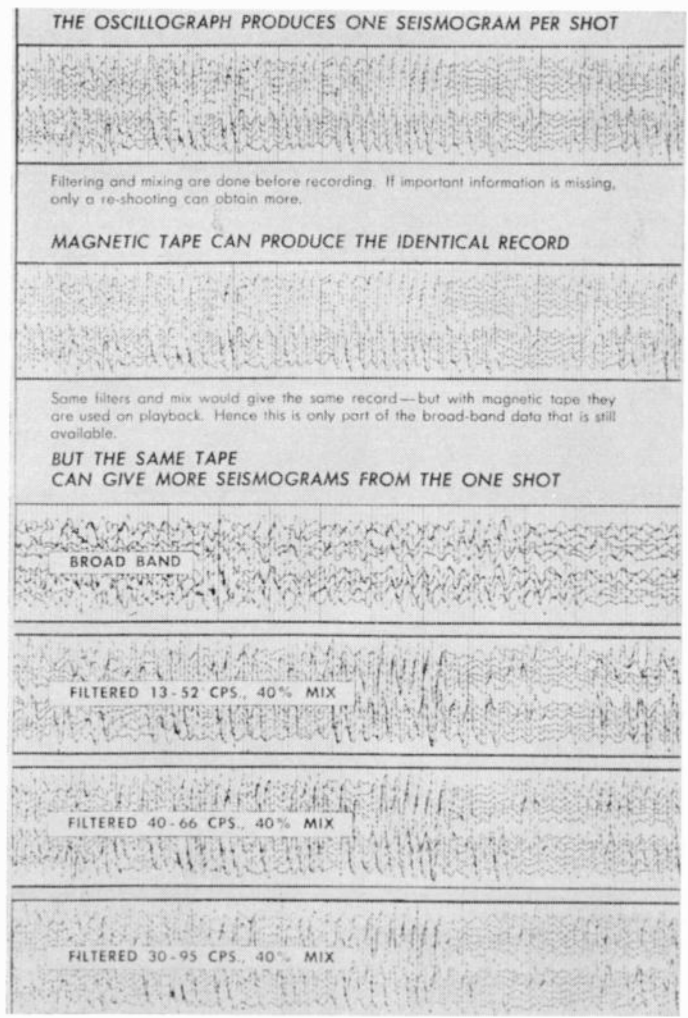


Fig. 28—Seismogram recording and analysis. (Ampex Corporation, Redwood City, Calif.)

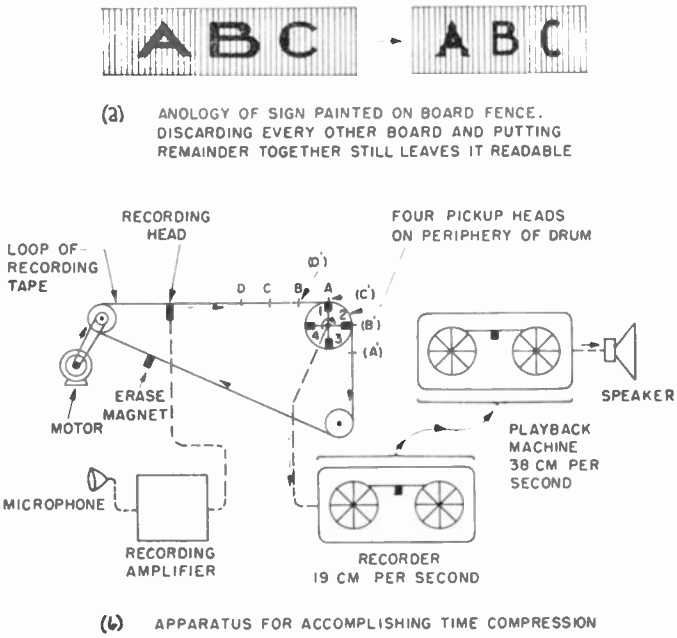


Fig. 29—The "Time-Compressor."

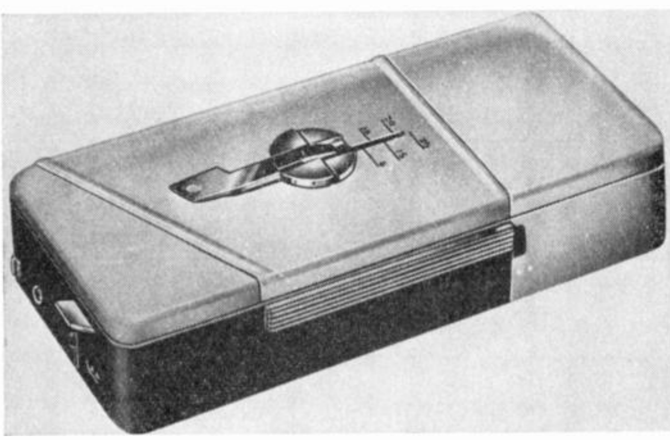


Fig. 30—Pocket-size tape recorder is a talking notebook. (Mohawk Business Machines, Brooklyn, N. Y.)

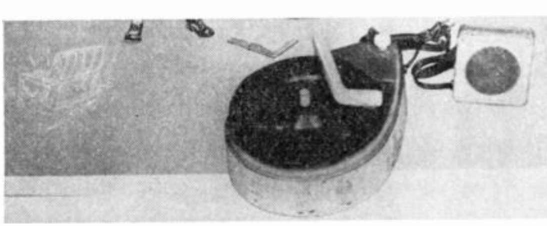


Fig. 31—Toy magnetic disc recorder. (General Electric Co., Syracuse, N. Y.)

Fig. 33. The words are recorded on a magnetic stripe on a file card. On top of the card is the printed word, symbols for pronouncing, definition, etc. For children it also shows a picture. For the blind, the word is printed in braille. A great many uses, including teaching of foreign languages are in store for the "Language Master."

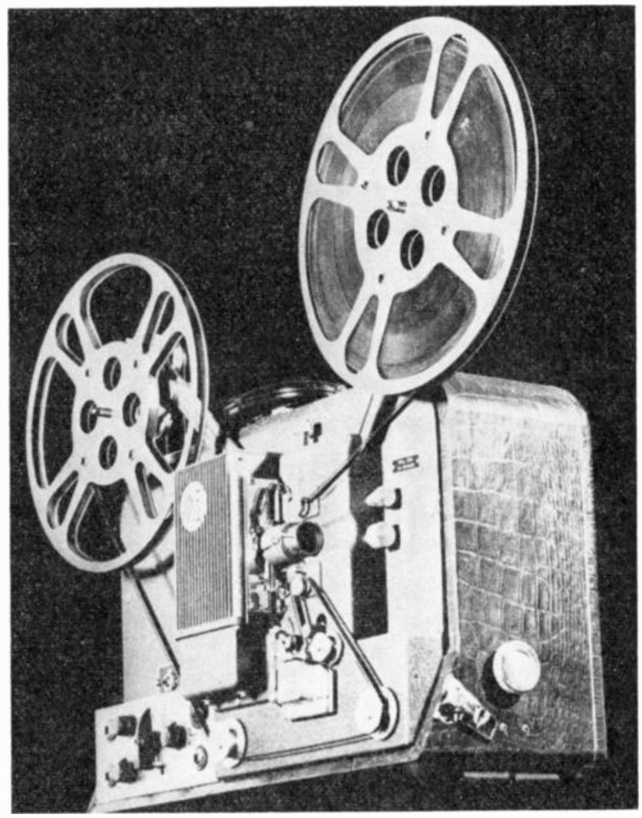


Fig. 32—Eight mm magnetic sound projector. (The Calvin Co., Kansas City 6, Mo.)

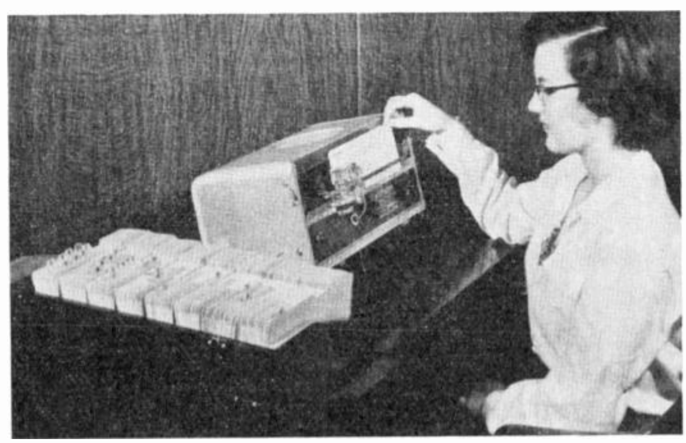


Fig. 33—The Language Master pronouncing dictionary. (McGraw-Hill, New York, N. Y.)

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Design Principles for Junction Transistor Audio Power Amplifiers*

D. R. FEWER†

Note: This is the last of a group of three tutorial papers on transistors, with special emphasis on use at audio frequencies, prepared by the Bell Telephone Laboratories Staff at the request of the editorial committee of the TRANSACTIONS ON AUDIO. Credit for organization of the papers goes to A. J. Grossman. The other two articles, "Properties of Junction Transistors," by R. J. Kircher, and "Design Principles of Junction Transistor Audio Amplifiers," by R. L. Trent, appeared in the July–August and September–October Transactions of the IRE on Audio.

***Summary*—Junction transistors may be employed as audio frequency power amplifiers which will supply up to several watts of output power. The fact that there are two basic types of transistor (*n-p-n* and *p-n-p*) allows a freedom of circuit design which is impossible with electron tubes.**

In power amplifier design the usual small signal assumptions cannot always be considered valid. Hence, large signal techniques must be applied in order to describe the behavior of the device. The nonlinear distortion associated with large signal operation is discussed in terms of the transistor characteristics and methods of reducing this distortion are outlined. Operation in several circuit connections is considered with particular emphasis on the common emitter configuration.

INTRODUCTION

THE FIRST PAPER of this series [1] has shown that junction transistors possess electrical characteristics which can be considered to be substantially linear provided operation is restricted to certain small regions. This restriction has made it possible to describe the device by means of small signal parameters and to represent it by means of equivalent circuits which contain linear elements. The small signal assumptions were used in the second paper of this series [2] in order to discuss the design of linear audio amplifiers.

In the case of power amplifiers, operation is usually beyond the limits that are assumed in small signal theory. Hence, it is necessary to extend the material included in the preceding papers to the case of large signal operation. Consideration will be given to such matters as distortion, efficiency and maximum working voltage which do not ordinarily arise in low-level amplifiers.

Many aspects of the small signal operation previously described [1, 2] apply, in principle, to large signal operation. Feedback and temperature compensation are examples. Low-frequency assumptions are considered valid.

Junction transistors may be employed successfully as audio frequency power amplifiers. As might be expected, they possess both advantages and disadvantages when compared with electron tube power amplifiers.

The main advantages are:

1. The sturdiness of construction makes the transistor less fragile than the electron tube.
2. When operated below the prescribed temperature limit the transistor is more efficient than the electron tube. The collector efficiency is high and in addition, no heater power is required.
3. For the same rated dissipation the present transistors are smaller than the electron tube.
4. Transistors will operate at voltages much lower than those required for electron tube operation.

The main disadvantages of the present transistors are:

1. The limited reverse collector voltage requires high currents for high power operation.
2. The efficiency of the device is highly dependent on ambient temperature.
3. The frequency cutoff of many units (particularly power transistors in the common emitter and common collector connection) is lower than that of electron tubes.
4. The present upper limit on power dissipation is comparatively low.

POWER TRANSISTORS

At the present time junction transistors are available which have been designed specifically to handle power. These power transistors are capable of dissipating up to several watts. Consequently, it is possible to build audio power amplifiers of considerable power output which take advantage of the desirable characteristics of transistors.

Construction

The main problem in designing transistors which will operate efficiently as power amplifiers is that of removing the heat resulting from unavoidable power losses. This is particularly important with transistors since the operating characteristics degrade at elevated temperature to such an extent that the maximum permissible operating temperature is relatively low. The semiconductor portion of the power transistor is constructed by standard techniques. Means are provided to conduct the heat generated in the transistor to an external connection, usually a metallic case. This thermal conduction is accomplished by one of two basic methods. A good metallic thermal and electrical conductor may be at-

* Manuscript received September 14, 1955.
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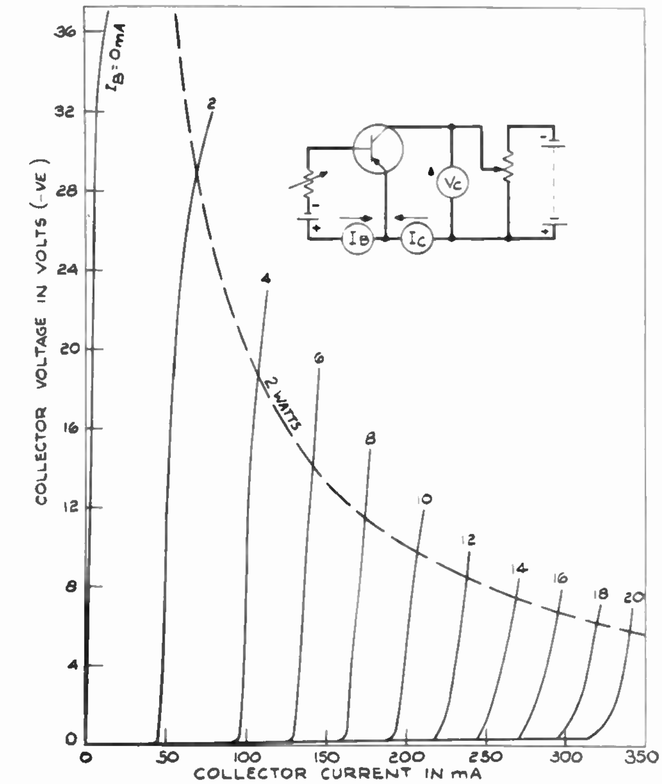

Fig. 1—2-watt power transistor output characteristic common emitter.

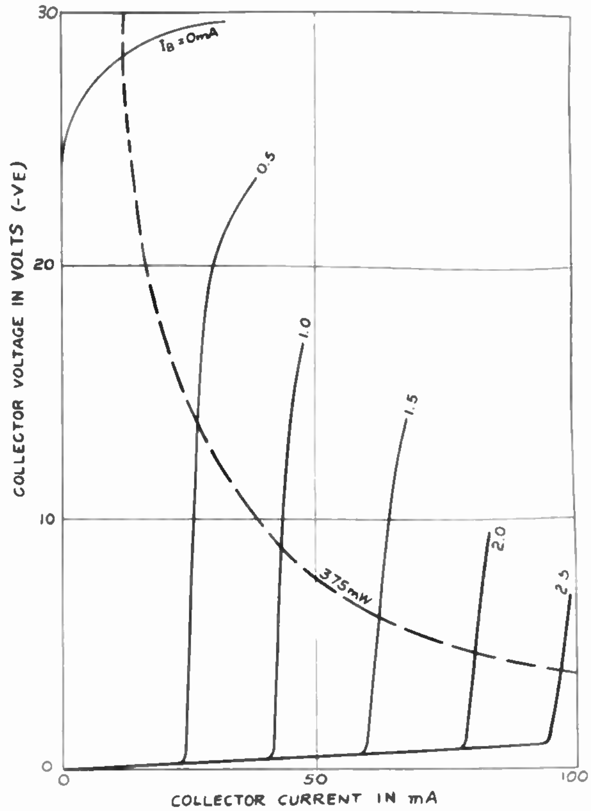

Fig. 2—375-mW power transistor output characteristics common emitter.

tached to one terminal of the transistor or the unit may be surrounded by a liquid which is a good thermal and a poor electrical conductor. The metallic conduction method presently predominates. The purpose of conducting the heat to the outside is to enable the unit to dissipate more power by the addition of an external heat sink. The power handling capacity of the device depends almost entirely upon the temperature difference between the semiconductor and the external connection and upon the effectiveness of the applied external heat sink. Most power transistors are of the junction type. Both fused alloy and grown junction, *n-p-n* and *p-n-p* types are made. Silicon and germanium are the semiconductor materials presently employed.

Electrical Properties

The increase in power handling capabilities generally means an increase in the size of the transistor.

This increase in size has the following implications:

1. The reverse breakdown voltage of the junction is relatively unchanged. Thus, increased power rating requires increased current handling capacity.
2. Current density is maintained within acceptable limits by the increase in cross-sectional areas.
3. Body resistance of the device is lowered and I^2R losses within the device are minimized.
4. Junction reverse leakage current is increased. This effect is not serious when operating at high currents within the temperature range of the device.
5. Depletion layer capacity is increased. The effect of this capacity is negligible for most audio frequency power amplifier applications.

Typical output characteristics of two germanium power transistors are shown in Fig. 1 and Fig. 2. The trend in power transistors is moving towards the use of silicon rather than germanium because of its more favorable temperature characteristics.

Characterization for Nonlinear Operation

Output Characteristics and Load Lines

The common base and common emitter output characteristics of an alloy junction transistor are shown in Figs. 3(a) and 3(b) respectively (next page). A comparison between these figures shows that the common base characteristics are more linear and display a more linear current gain to high collector currents, have sharper "knees" at the peak inverse voltage, have lower leakage and have a higher open circuit output resistance (r_{22}) than those of the common emitter.

In general, four properties determine the limits of operation.

1. The peak collector voltage is limited by the peak inverse voltage of the transistor.
2. The maximum collector current is limited by the reduction in the current gain at high values of collector current.
3. The power dissipated in the device must not exceed the rated value.

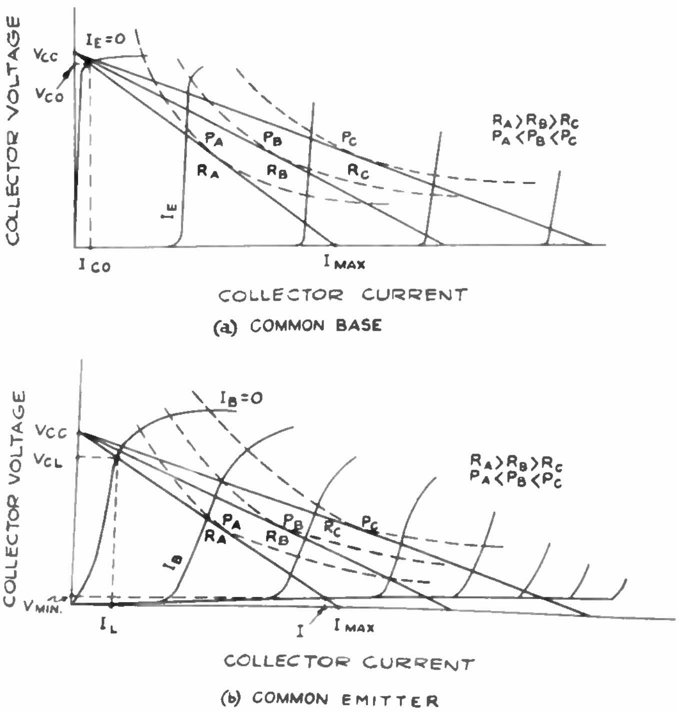

Fig. 3—Output characteristics.

4. The minimum collector current is determined by the collector leakage current.

In order to increase the power rating of an alloy junction transistor it is usually not possible to increase the collector voltage beyond the breakdown value. Hence an increase in power rating, as indicated by the hyperbolas of constant power P in Fig. 3, requires that the transistor carry larger currents. The result is that the load resistance must decrease when the output power increases. This effect is indicated by the values of R in Fig. 3. For high power operation which necessitates the use of a load resistance which is low compared to the output resistance of the transistor the power gain is comparatively small and is approximately proportional to the load resistance.[1]

The greater linearity of the common base characteristics allows higher power operation for a fixed upper limit on distortion. The useful portion of the load line which determines the power available to the load, and hence the efficiency, is greater for common base operation. Fig. 3(a) shows that the useful portion of the load line extends from the points (V_{c0}, I_{c0}) to approximately $(O, I_{\max})$ where $V_{c0} \cong V_{cc}$ and $I_{\max} - I_{c0} \cong I_{\max}$. Fig. 3(b) shows that the above approximations cannot be considered valid in the common emitter connection where useful operation extends between the points (V_{CL}, I_L) and $(V_{\min}, I)$.

Input Characteristics

The common emitter input characteristic family with collector voltage as the parameter is in Fig. 4. The reciprocal of the slope of these curves at any point is the small signal short-circuit input resistance h_{11}.[2] The important properties of the input characteristic family are:

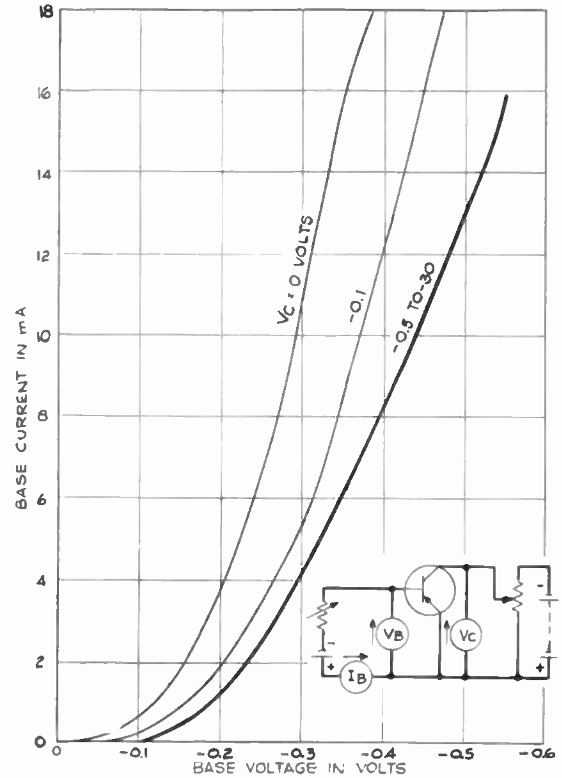

Fig. 4—Input characteristic family—common emitter.

1. The input resistance is high and very nonlinear for low values of input bias current.
2. The input resistance is relatively independent of collector voltage, for collector voltage greater than a few tenths of a volt.

The input resistance is relatively unaffected by changes in collector voltage over the normal working range of transistor power amplifiers. Hence the small signal values of dynamic input resistance (R_{IN}) and the short circuit input resistance (h_{11}) may be assumed to be equal [2]. It is shown in Appendix I that when the collector voltage is neglected the base to emitter voltage of a common emitter stage may be expressed as a function of base current:

$$V_B \cong I_B r_b + \frac{kT}{q} \ln \left[\frac{I_B}{(1-\alpha')I_{ES}} \right]. \qquad (1)$$

For comparison, the measured and calculated input characteristic curves for an alloy junction power transistor are shown in Fig. 5.

From the above equation it is seen that the relationship between input voltage and input current contains

[1] The load resistance should equal the transistor output resistance for maximum power transfer from the transistor to the load.

[2] The terms, r, g, h, with a double subscript, are used to denote the small signal parameters as discussed in the previous papers [1, 2].

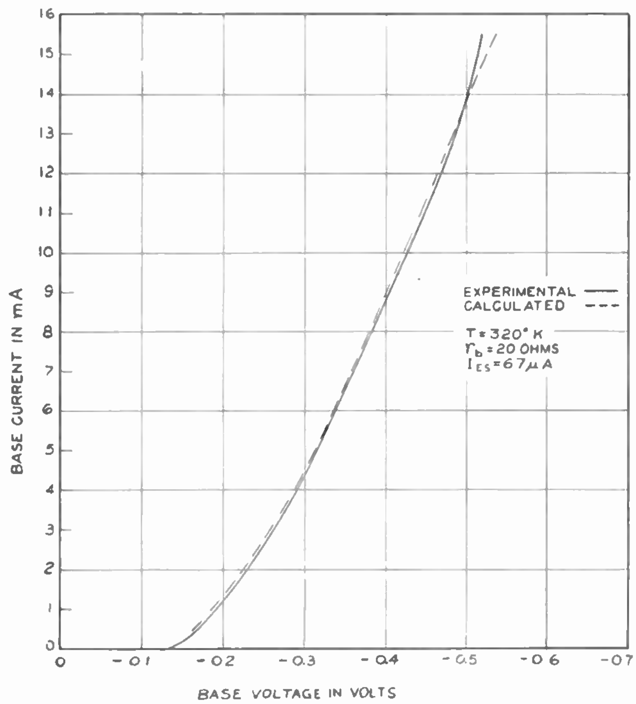

Fig. 5—Input characteristic—experimental and calculated.

both a linear and a logarithmic term. When resistance is added externally in series with the base or the emitter the effect is to increase the linear term and hence produce a more linear input characteristic.

Transfer Characteristics

The input and output characteristics of a transistor are related by its transfer properties. The most important transfer characteristics are:

1. The dynamic input current-output current or current transfer characteristic.
2. The dynamic input voltage-output current or trans-conductance characteristic.

Common emitter dynamic transfer characteristics for a fused alloy transistor are shown in Figs. 6 and 7. The transfer characteristics are relatively independent of the load for many transistors in power output applications. The slope of the current transfer characteristic approximates the short circuit current gain h_{21} and the slope of the transconductance characteristic approximates the transconductance g_{21}.

Transfer characteristics are useful in evaluating the performance of the transistor as an amplifier. The characteristic one should use depends upon the relationship between the driving source resistance (R_G) and the input resistance of the transistor (R_{IN}). When $R_G \gg R_{IN}$ the transistor is driven by a source which supplies essentially a constant current. When this occurs the current transfer characteristic may be used to examine the amplifier performance. When $R_G \ll R_{IN}$ the transistor is driven by a constant voltage source. In this case the transconductance characteristic is used. In general, the most useful characteristic depends upon whether the driving source waveform is reproduced at the transistor input as a current or a voltage.

When the driving generator cannot be considered either a constant voltage or a constant current source it is convenient to consider it as a constant voltage generator (v_g) supplying for example, a common emitter stage with a base resistance $R_B = r_b + R_G$ (where v_g and R_G are, respectively, the equivalent generator voltage and internal resistance obtained by Thevenin's theorem). Fig. 8 shows the emitter E, base B, and collector C connections to the composite transistor. A composite transconductance characteristic is now defined as the variation of collector current with generator voltage. The slope of this characteristic may be expressed in terms of the short circuit input resistance h_{11}, the transconductance g_{21}, and the generator internal resistance R_G by

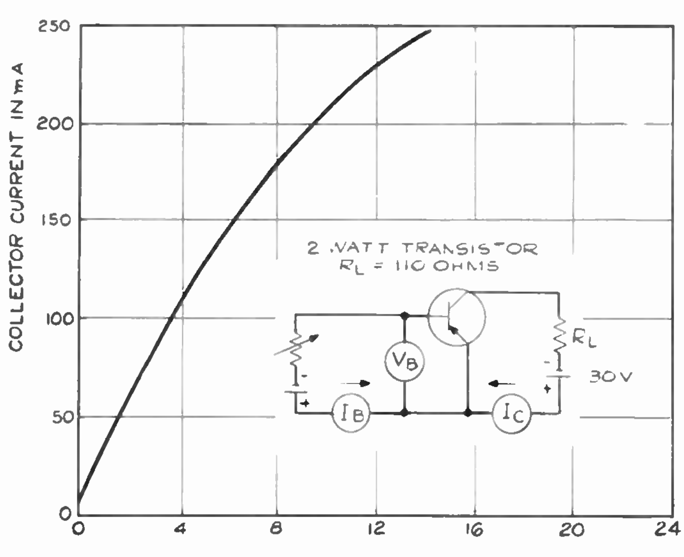

Fig. 6—Common emitter dynamic current transfer characteristic.

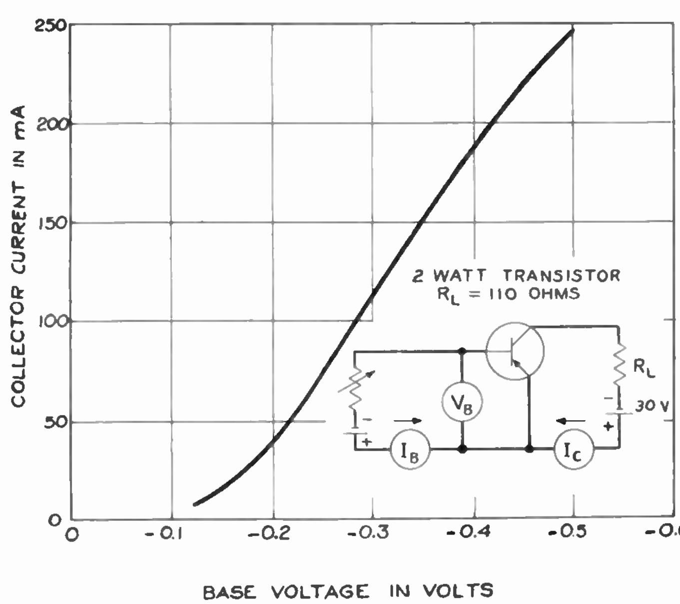

Fig. 7—Common emitter dynamic transconductance characteristic.

$$g_{21}' = \frac{g_{21}h_{11}}{R_G + H_{11}}. \quad (2)$$

Graphical Analysis

Dynamic characterization of a transistor under the actual conditions of circuit operation produces results which may be treated graphically to evaluate, quantitatively, many of the properties of the device as a power amplifier. Standard electron tube methods of graphical analysis [3–5] are readily applicable to transistor curves obtained in this manner.

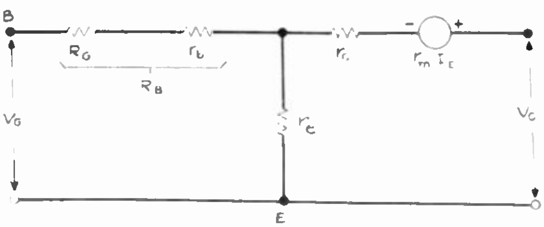

Fig. 8—Composite transistor.

Class A Operation

In the following sections Class A common emitter audio frequency power amplifiers are discussed. The general discussion also pertains to common base and common collector operation.

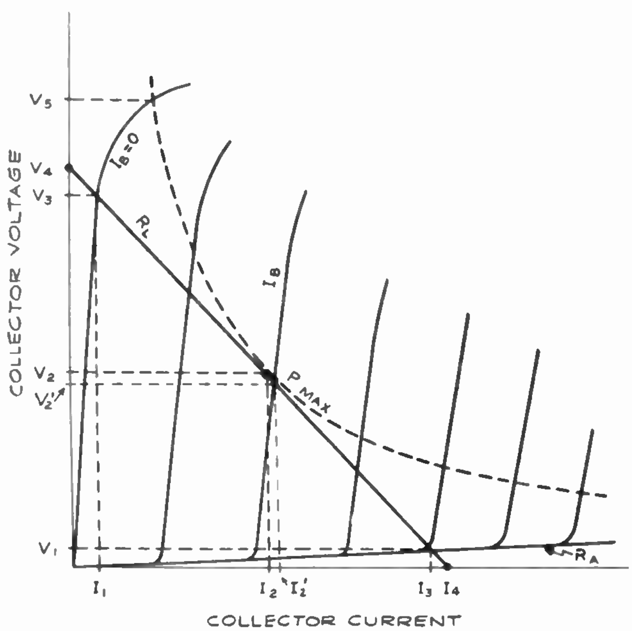

Fig. 9—Collector static characteristics for common emitter—Class A operation.

Static Characteristic Analysis of Class A Operation

Analysis of Class A operation of transistors employed as power amplifiers may be carried out by means of transfer characteristics. A more complete analysis, however, is obtained from the static output characteristic. Typical collector characteristics are shown in Fig. 9. These curves are drawn for the common emitter connection with base current as parameter. The maximum allowable collector dissipation is shown as a rectangular hyperbola P_{max}. The points of interest for Class A operation are:

V_5—Represents an upper limit on collector voltage where the device is dissipating the maximum allowable power due to collector leakage current.

V_4—This is the voltage at which the load line R_L intersects the voltage axis. It is determined by the linearity and efficiency requirements on the amplifier. When R_L is a dc load line this voltage is the collector supply voltage. The load line for maximum load resistance is drawn through this point, tangent to the P_{max} hyperbola. The construction of a load line establishes the other points of interest.

V_3, I_1—This is the point on the load line where the collector leakage current fixes an upper limit on the collector voltage. It is the point where the $I_B=0$ curve cuts the load line.

V_2, I_2—This is the point where the load line is tangent to the power hyperbola. It is the midpoint of the load line and approximates the dc operating point for Class A operation.

V_1, I_3—This is the point on the load line where the voltage drop across the transistor (represented by the line R_A) sets an upper limit on the collector current.

I_4—Represents the collector current maximum. It is fixed by the load line and collector voltage maximum. When it is desirable to design from this point, the load line may be established as a line through I_4 tangent to P_{max} (collector voltage permitting) or as a line joining I_4 and V_4 (maximum power permitting). Conditions on the linearity of current gain will fix the upper value of I_4.

In general, any load line drawn tangent to the P_{max} hyperbola is permissible provided the conditions fixed for V_4 and I_4 are not violated. For optimum operating conditions the dc operating point should be adjusted so that:

$$I_2 - I_1 = I_3 - I_2. \quad (3)$$

The maximum ac output power is:

$$P_{ac} = \frac{(I_2 - I_1)(V_2 - V_1)}{2}. \quad (4)$$

The dc power supplied to the collector is:

$$P_{dc} = V_2I_2. \quad (5)$$

The collector efficiency is:

$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{V_2I_2 - V_2I_1 - V_1I_2 + V_1I_1}{2V_2I_2}. \quad (6)$$

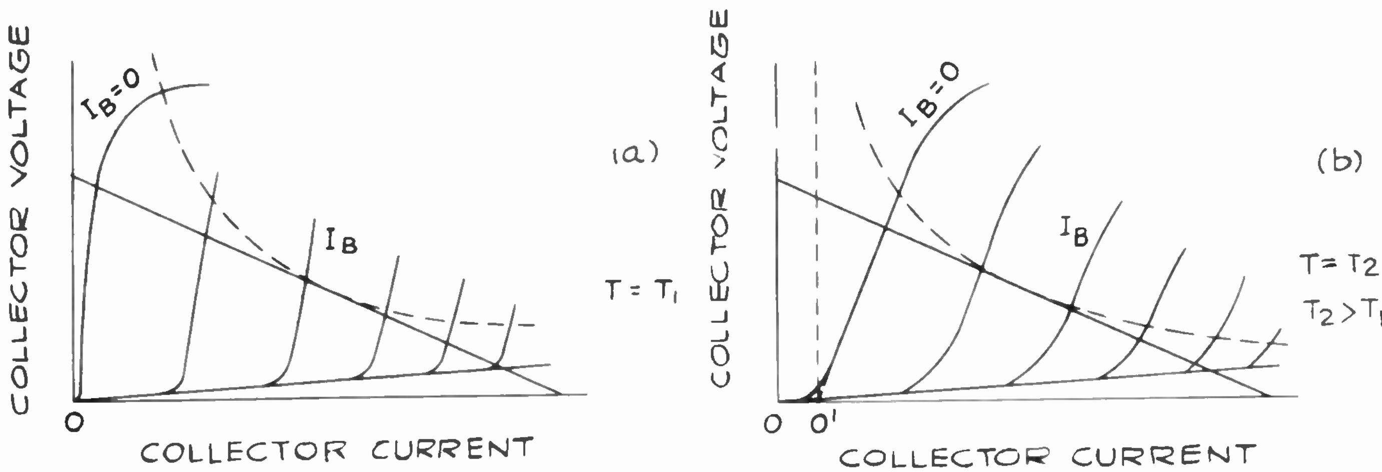

Fig. 10—Output characteristics—temperature effects.

For many transistors $V_1 \ll V_2$ and so

$$\eta \cong \frac{I_2 - I_1}{2I_2}. \tag{7}$$

The theoretical upper limit of the efficiency for Class A operation is obtained by letting I_1 and V_1 go to zero. This gives:

$$\eta = 50 \text{ per cent.} \tag{8}$$

When transistors possess nonlinear transfer properties the requirement given in (3) (*i.e.*, symmetrical output current swing about an operating point, I_2) can be satisfied only by an asymmetrical input waveform. Consider the output characteristic family shown in Fig. 9 where the parametric lines I_B represent equal changes in base current. I_2' represents the collector current corresponding to a base current which is one-half the total base current swing necessary to vary the collector current over the range I_1 to I_3. The fact that I_2 and I_2' do not coincide signifies that the current transfer through the device is nonlinear. When I_2 and I_2' do not coincide it is not possible to specify uniquely an optimum operating point. Consideration must be given to gain, distortion and efficiency which vary with the point of operation. The general design practice is to compromise by operating with a collector current somewhere between I_2 and I_2'.

Operation at High Temperature

The effect of high operating temperature on an amplifier stage has been discussed in the previous papers of this series [1, 2]. The effect of increasing the temperature on the output characteristics is illustrated in Fig. 10. The higher temperature lowers the output resistance and shifts the collector current, for the same base current, to larger values. These two effects combine to make less of the load line available for current and voltage swings. This decreases the efficiency.

Static output characteristic analysis may be applied in the same manner as previously described by shifting the collector current axis origin from O to O'. In this case the length OO' equals the increase in collector leakage current due to elevated temperature. Using I' for the modified values of collector current measured from the origin O' the general expression for efficiency becomes:

$$\eta = \frac{V_2I_2' - V_2I_1' - V_1I_2' + V_1I_1'}{2V_2(I_2' + OO')}. \tag{9}$$

Distortion

There are three major contributing factors causing nonlinear distortion in the output waveform of a transistor power amplifier stage. These factors are interdependent to a certain degree but may be listed:

1. Input nonlinearities.
2. Output limiting or clipping.
3. Transfer nonlinearities.

The nonlinear input resistance of the device is discussed in Appendix I. Current distortion at the input may be minimized by driving the transistor from a high impedance source. Input voltage distortion may be minimized by driving the transistor from a low impedance source. Output circuit limiting or clipping occurs when the transistor is overdriven and excursions about the operating point are large enough to cause clipping at one or both ends of the load line. This type of distortion may be reduced or eliminated by a shift in the operating point and/or a reduction in signal amplitude. When the input waveform is considered undistorted and limiting or clipping does not occur at the output it is possible to evaluate, quantitatively, the performance of the device as a power amplifier from its transfer characteristics.

Conventional electron tube procedures [3, 4] for evaluating device performance involve the analysis of the dynamic plate current-grid voltage transconductance characteristic. The analysis is facilitated by the fact that the input waveform is essentially independent of the driving source impedance. This is due to the fact that the input impedance to the electron tube may be considered infinite at audio frequencies. Similar procedures may be employed in the analysis of transistor power amplifiers. However, the choice of transfer characteristic depends on the relationship between the source impedance (R_G) and the transistor input impedance (R_{IN}) as previously discussed.

Case I $R_G \gg R_{IN}$

The transistor is characterized dynamically such that the output current I_2 is determined as a function of the input current I_1. If an operating point on the curve is selected then the change ΔI_2 of I_2 due to a change ΔI_1 of I_1 may be determined by a Taylor Series expansion about the operating point as follows:

$$\Delta I_2 = \frac{dI_2}{dI_1}\Delta I_1 + \frac{1}{2!}\frac{d^2I_2}{dI_1^2}(\Delta I_1)^2 + \frac{1}{3!}\frac{d^3I_2}{dI_1^3}(\Delta I_1)^3 + \cdots, \quad (10)$$

where ΔI_1 and ΔI_2 are measured from the operating point.

If the slope of the dynamic current gain characteristic at the operating point is defined as b_{21} then (10) may be written:

$$i_2 = b_{21}i_1 + \frac{1}{2!}\frac{db_{21}}{dI_1}i_1^2 + \frac{1}{3!}\frac{d^2b_{21}}{dI_1^2}i_1^3 + \cdots, \quad (11)$$

where

$$i_1 = \Delta I_1 \quad \text{and} \quad i_2 = \Delta I_2.$$

Case II $R_G \ll R_{IN}$

The dynamic transconductance characteristic, which shows the dependence of the output current I_2 on the input voltage V_1, may be treated in a similar fashion to the current transfer characteristic. If the slope of the characteristic at the operating point is t_{21}, a change in output current i_2 may be written as a function of the input voltage change v_1:

$$i_2 = t_{21}v_1 + \frac{1}{2!}\frac{dt_{21}}{dV_1}v_1^2 + \frac{1}{3!}\frac{d^2t_{21}}{dV_1^2}v_1^3 + \cdots. \quad (12)$$

Case III $R_G \cong R_{IN}$

The composite transistor technique, previously discussed, may be used in the case where the generator impedance is of the order of the transistor input resistance. The dynamic transconductance characteristic shows the dependence of output current I_2 on the generator voltage V_G. If t_{21}' is the slope of the characteristic at the operating point, the change in output current i_2 may be written as a function of generator voltage change v_g:

$$i_2 = t_{21}'v_g + \frac{1}{2!}\frac{dt_{21}'}{dV_G}v_g^2 + \frac{1}{3!}\frac{d^2t_{21}'}{dV^2_G}v_g^3 + \cdots. \quad (13)$$

The dynamic characteristics discussed above are useful for specific applications when the driving source and load are defined. A more general approach requires that the analysis of the transistor performance be made independent of external connections. This is shown for a common emitter stage in Appendix II. The results indicate that for particular transistors, the approximate base and collector currents may be written:

$$i_b \cong g_{11}v_b + \frac{1}{2}\frac{\partial g_{11}}{\partial V_B}v_b^2 \quad (14)$$

$$i_c \cong \frac{h_{21}}{K_1}i_b + \frac{1}{2K_1}\frac{\partial h_{21}}{\partial I_B}i_b^2, \quad (15)$$

where

$$K_1 = 1 + R_L/r_{22}.$$

Comparison between (11) and (15) show that for a second-order expansion:

$$b_{21} = \frac{h_{21}}{K_1} \quad (16)$$

or, when

$$R_L \ll r_{22}$$

$$b_{21} \cong h_{21}. \quad (17)$$

The collector current may also be written:

$$i_c \cong \frac{g_{21}}{K_2}v_b + \frac{1}{2K_2}\frac{\partial g_{21}}{\partial V_B}v_b^2, \quad (18)$$

where

$$K_2 = 1 + g_{22}R_L$$

or, when

$$R_L \ll 1/g_{22}$$

$$t_{21} \cong g_{21}. \quad (19)$$

When (14) is substituted in (15) and terms of higher order than the second are neglected, the expression for the collector current for a common emitter power amplifier stage becomes

$$i_c \cong \frac{h_{21}g_{11}}{K_1}v_b + \frac{1}{2K_1}\left[h_{21}\frac{\partial g_{11}}{\partial V_B} + g_{11}^2\frac{\partial h_{21}}{\partial I_B}\right]v_b^2. \quad (20)$$

The collector current may also be written as a function of generator voltage by a similar substitution.[3]

$$i_c \cong \frac{h_{21}g_{11}'}{K_1}v_g + \frac{1}{2K_1}\left[h_{21}\frac{\partial g_{11}'}{\partial V_G} + g_{11}'^2\frac{\partial h_{21}}{\partial I_B}\right]v_g^2. \quad (21)$$

The second-order collector current distortion may be determined by the magnitude of the coefficient of v_b^2 in

[3] The base current may be written as a function of generator voltage

$$i_b = g_{11}'v_g + \frac{1}{2}\frac{\partial g_{11}'}{\partial V_G}v_b^2 + \cdots,$$

where g_{11}' is the input conductance of the composite transistor discussed in the second section.

(20). The quantity

$$\left[h_{21}\frac{\partial g_{11}}{\partial V_B} + g_{11}^2\frac{\partial h_{21}}{\partial I_B}\right]$$

may be analyzed graphically to determine the effect of the input and current transfer properties of the device on the output current. A qualitative graphical analysis is shown on Fig. 11. The points marked x indicate the quiescent operating points. The values of g_{11} and h_{21} and their derivatives at the operating points are those which should be substituted in (20) or (21). From the curves shown in Fig. 11 it is seen that the quantities g_{11}, h_{21}, and $\partial g_{11}/\partial V_B$ are positive while $\partial h_{21}/\partial I_B$ is negative. The proper balance of these quantities makes it possible to reduce second-order distortion considerably.

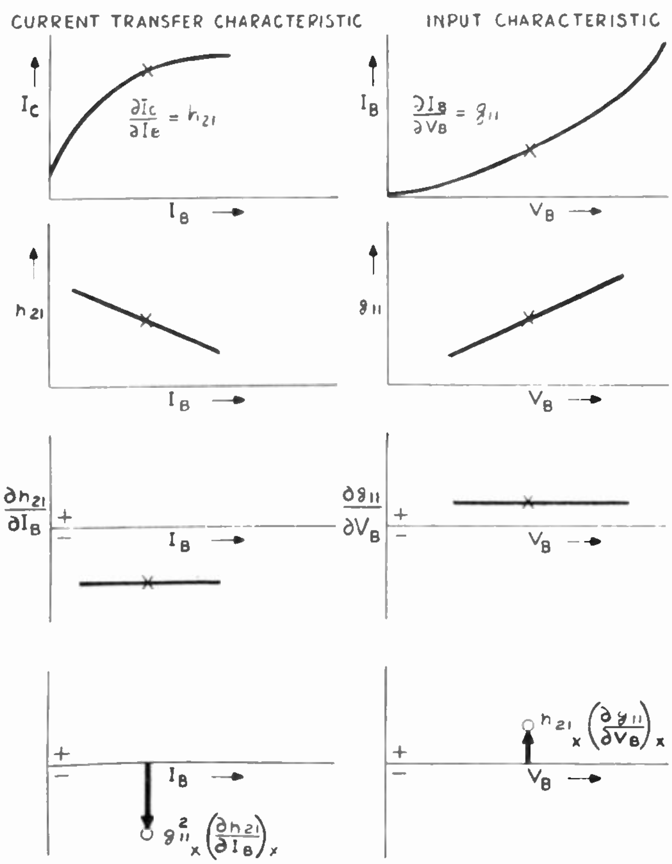

Fig. 11—Input-output distortion effects common emitter operation.

In practice, the term $\partial g_{11}/\partial V_b$ is small in the operating range due to the linearization effect of the base resistance on the input characteristic. Base resistance added externally as generator resistance further linearizes the input characteristic so that the value of $\partial g_{11}'/\partial V_G$ in (21) decreases and second-order distortion increases. This effect is illustrated in Fig. 12 where output second-harmonic distortion is plotted as a function of generator resistance. The results shown in this figure apply to transistors having characteristics similar in shape to those shown in Figs. 5 and 6. In general the term $\partial g_{11}/\partial V_B$ is positive but the term $\partial h_{21}/\partial I_B$ may be either positive or negative depending on the type of transistor employed. When $\partial h_{21}/\partial I_B$ is positive the second-order distortion is minimized when the transistor is supplied from a high resistance source.

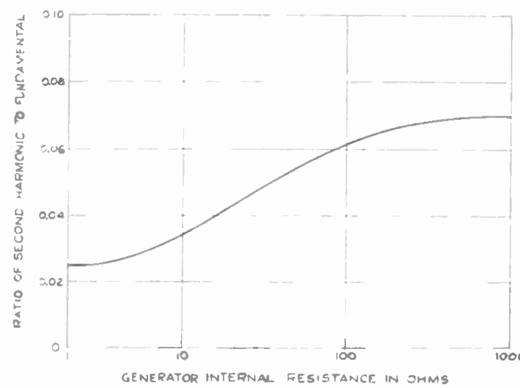

Fig. 12—Effect of driving source resistance on output distortion.

When the transistor is driven in such a manner that the input current swing extends far into the low current, nonlinear portion of the input characteristic it is always advisable to use a high resistance driving source. In this region the $\partial g_{11}'/\partial V_G$ term may become very large unless a large generator resistance is used.

Output Stage Gain Considerations

Gain considerations for transistors employed as low level amplifiers were discussed in the previous papers of this series. These low level gain expressions may be applied to determine approximately the behavior of transistors employed as power amplifiers. For many applications some approximations are allowable due to the comparatively high current levels at which the device is operated. The performance of the output stage transistor in terms of the small signal hybrid (h) parameters is outlined in Appendix III.

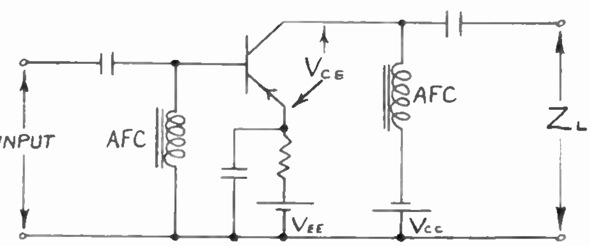

Fig. 13—Class A output stage.

A schematic diagram of a single ended Class A power output stage is shown in Fig. 13. The circuit employs bias stabilization [2]. Shunt feed is used to prevent the collector bias current from flowing in the load.

Class A Push-Pull Operation

A great deal of the distortion caused by nonlinearities in the dynamic transfer characteristics of transistors may be eliminated by means of a push-pull circuit arrangement such as that shown in Fig. 14. In this circuit the driving signal is introduced through a center-tapped transformer. Any other circuit which provides two equal inputs which differ in phase by 180° may be used.

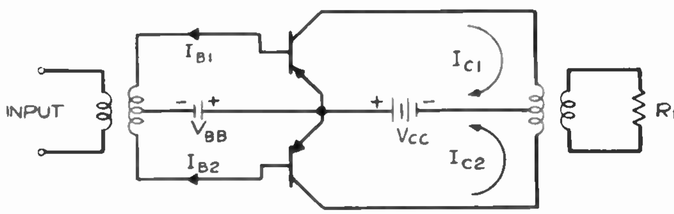

Fig. 14—Push-pull circuit.

Fourier series analysis shows that this type of circuit balances out all even harmonics at the output provided the transistors are identical over the range of operation. Odd harmonics are present and the third harmonic becomes the principal source of distortion.

The selection of matched transistors for push-pull operation involves both their static characteristics and frequency response. It is advisable to employ units with frequency cutoffs greater than a decade above the highest frequency of interest.[4] For many of the higher power transistors in the common emitter connection, the frequency cutoff may be as low as 10 to 15 kc. Under this condition transistors should be chosen for similarity of frequency response.

Reference to Fig. 14 shows that the steady components of the collector current oppose each other magnetically in the output transformer core. This eliminates any tendency towards core saturation and consequent nonlinear distortion which might arise due to the curvature of the transformer magnetization curve.

An equivalent circuit of the common emitter push-pull Class A connection is shown in Appendix IV in which the equivalent circuit of a push-pull Class A amplifier is discussed.

Since the push-pull circuit balances out even harmonics the magnitude of the input swing is limited mainly by the allowable third harmonic component in the output. A graphical construction must be employed to take account of the nonlinearity of the transistor characteristics. Static and dynamic characterization may be carried out by standard electron tube procedures [5]. Fig. 15 shows a representative set of output characteristics for two identical transistors and the irresultant composite output characteristic for Class A common emitter push-pull operation.[5] The curves O_1 and O_2 are the paths of operation of transistors $T1$ and $T2$ respectively, for the load line $R_L'/4$ (Appendix IV). The points $Q1$ and $Q2$ are the quiescent operating points. The point Q is the composite quiescent operating point. The curves show the effect of the reverse collector breakdown voltage "knees" on the composite characteristic. This effect is further illustrated in Fig. 16 which shows the composite dynamic current transfer characteristic. Operation at voltages sufficiently high to drive the collector into the region of the "knee" can cause severe distortion and should be avoided.

[4] The phase shift of a transistor is approximately 6° at a frequency which is one-tenth the cutoff frequency.

[5] The decrease of collector resistance with increase in collector current is not considered in this and subsequent treatments. This phenomenon is discussed in a previous paper of this series [1].

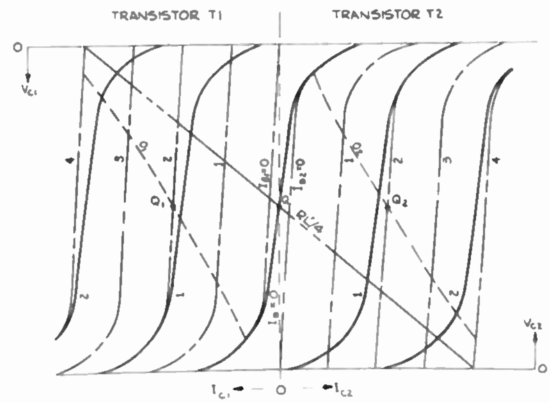

Fig. 15—Composite push-pull static output characteristics.

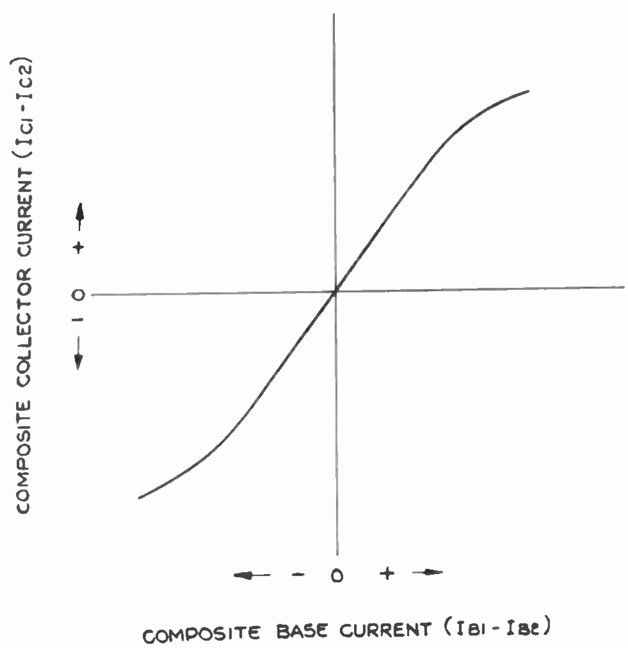

Fig. 16—Composite push-pull dynamic transfer characteristic—Class A operation.

Class B Push-Pull Operation

When a transistor is biased at collector current cutoff so that the current flows exactly for one-half cycle during alternate half-cycles it is said to be operating under Class B conditions. The nature of the operation requires that the transistor be operated in a push-pull circuit. The circuit configurations for Class B push-pull operation are the same as those shown for Class A. The chief advantage of a Class B system is its greater power output compared to the Class A system. This is due to the higher collector circuit efficiency. Also, while the Class A system dissipates maximum power for the no signal condition, the Class B system requires very low standby power.

Nonlinear distortion is greater with Class B operation than with Class A. There is a cancellation of the even-order harmonics in the output as with Class A but additional nonlinearities are introduced due to "join-up" or "crossover" effects.

The composite characteristics for Class B common emitter operation are drawn in the same manner as those shown for the Class A case in Fig. 15. The quiescent points, however, lie on the respective $I_B = 0$ curves for each transistor. For accurate representation the curves for reverse input current bias should be taken into account. The net result of composite characterization is a set of characteristics which are essentially coincident with the individual transistor collector characteristic over their linear portion. In the region of the "knee" of the collector voltage the composite characteristic is similar in shape to the composite Class A characteristic.

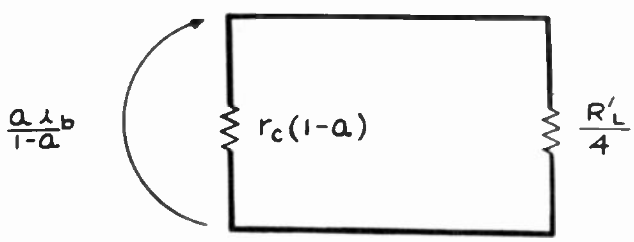

Fig. 17—Class B push-pull output equivalent circuit.

When transistors with low leakage current are operated in Class B push-pull amplifiers the two circuit halves carry current in alternate half cycles. If the two halves are identical and work alternately then they can be represented by either one working alone continuously. The equivalent output circuit for the common emitter push-pull Class B power amplifier may be represented by that shown in Fig. 17. The equivalent output resistance is seen to be equal to that of a single transistor.

In drawing the equivalent circuit of an amplifier which is expected to develop large signal swings it is a necessary approximation to consider the resistances as constant in value. These constant values are usually the small signal values measured at the quiescent operating points. Reference to Fig. 15 shows that a Class B composite characteristic passing through the quiescent operating point will have a slope $r_{c0}(1-\alpha)/2$. Thus, the output resistance of a Class B common emitter audio frequency power amplification stage may range approximately as follows:

$$r_c(1 - \alpha) < R_0 < \frac{r_{c0}(1 - \alpha)}{2}. \qquad (22)$$

Class B Amplifier Design

Consider the output characteristic shown in Fig. 18. The load line for Class B operation is drawn between the points V and I. Output transformer coupling requires that the transistor withstand a peak output voltage of $2V$ so that the voltage V is selected to be one-half the maximum allowable transistor voltage. With the point V selected the maximum dissipation of the transistor determines the slope of the load line for maximum power and hence the point I. The half-sinusoid variation of V_2 and I_2 is identical with that of a half-wave rectifier. At maximum signal the average dissipation of the output circuit per transistor is:

$$P_{ave} = \frac{VI}{\pi}. \qquad (23)$$

The ac output power from a push-pull Class B pair is:

$$P_{AC} = \frac{VI}{2}. \qquad (24)$$

Since both transistors operate identically the ac power contributed to the load from one transistor is:

$$P_{ac} = \frac{VI}{4}. \qquad (25)$$

The efficiency for ideal Class B operation is:

$$\eta = \frac{P_{ac}}{P_{ave}} = \frac{\pi}{4}. \qquad (26)$$

The load resistance from Fig. 18 is:

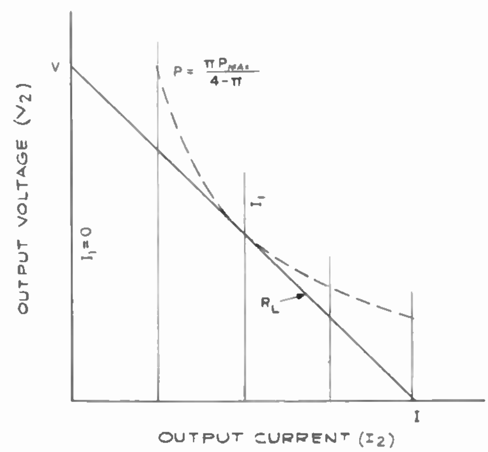

Fig. 18—Output characteristic for Class B operation.

$$R_L = \frac{V}{I}. \qquad (27)$$

The power dissipated in the transistor is:

$$P_D = P_{ave} - P_{ac} \qquad (28)$$

or

$$P_D = P_{ac}\left(\frac{1 - \eta}{\eta}\right). \qquad (29)$$

From Fig. 18 it is seen that the load line is tangent to the power hyperbola of power $VI/4$ which is also the value of the ac power per transistor delivered to the load. If P_{max} is the maximum allowable transistor dissipation the maximum ac power per transistor which may be delivered to the load is:

$$P_{ac} = \frac{\eta}{1-\eta} P_{max}. \tag{30}$$

This indicates, in the ideal case, that the load line is drawn tangent to the power hyperbola which represents the power:

$$\frac{VI}{4} = \frac{\eta P_{max}}{1-\eta} \tag{31}$$

or,

$$\frac{VI}{4} = \frac{\pi P_{max}}{4-\pi} \tag{32}$$

$$I = \frac{8\pi P_{max}}{(4-\pi)V_{max}}. \tag{33}$$

Since

$$2V = V_{max}$$

or

$$I = 29.2 \frac{P_{max}}{V_{max}}. \tag{34}$$

In many cases, particularly for the common emitter and common collector connections, the useful portion of the load line is less than that indicated in Fig. 18. The

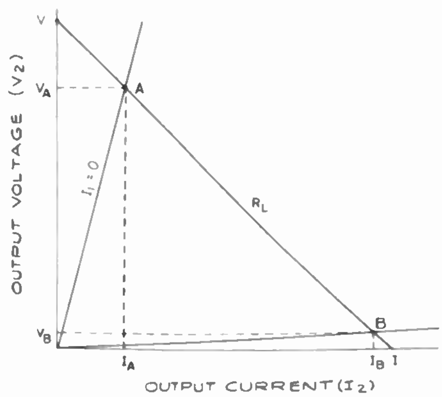

Fig. 19—Output characteristic showing low efficiency Class B operation.

general case is illustrated in Fig. 19 where the distance AB is the useful portion of the load line. The maximum ac power delivered to the load from a single transistor of the push-pull pair is:

$$P_{ac} = \frac{(V_A - V_B)(I_A - I_B)}{4}. \tag{35}$$

The power dissipated in the output circuit for maximum signal swing is:

$$P_{ave} = V_A I_A + \frac{4}{\pi} P_{ac}. \tag{36}$$

The efficiency becomes:

$$\eta = \frac{\pi P_{ac}}{\pi V_A I_A + 4P_{ac}}. \tag{37}$$

With transformer output the load line represents one-quarter of the resistance across the transformer primary. Due to the extreme nonlinearity of the input resistance of the transistor it is difficult to assess its value for Class B operation. In many practical high power cases, however, the input resistance for large signal swing is approximately equal to the input resistance for Class A operation. When an input transformer is used the input resistance of a single transistor of the push-pull Class B pair is one-quarter of the resistance across the transformer secondary. If R_{IN} is the input resistance and R_L is the effective load resistance of a single transistor of a push-pull Class B stage then the approximate gain of the stage is:

$$G \cong A^2 \frac{R_L}{R_{IN}} \tag{38}$$

where

$$A = \frac{h_{21}}{1 + h_{22}R_L},$$

the current gain. A design of a common base push-pull Class B power amplifier is shown in Appendix V.

Distortion in Class B Amplifiers

There are four major causes of distortion in Class B push-pull power amplifiers.

1. The transistors may possess low frequency cutoffs which differ. A mismatch results in even order harmonic distortion.

2. Similar characteristics which are nonlinear cause odd order harmonic distortion.

3. A difference in transistor characteristics which may cause unequal gains produces serious even order harmonic distortion.

4. Improper biasing may cause extremely large odd order harmonic distortion.

Items 2, 3 and 4 are the major causes of distortion in Class B push-pull audio frequency power amplification stages. Fig. 20 shows the transfer characteristics for Class B common emitter operation. The type of biasing shown is known as biasing to projected cutoff. The composite characteristic in the region of crossover is linear under these conditions. For large collector currents the composite characteristic is curved and causes the distortion mentioned in (2) above. Poor regulation in the Class B amplifier bias supply may also be the cause of this type of nonlinear distortion. As stated in (23) the average power required from the collector bias supply is proportional to the output signal amplitude. When the

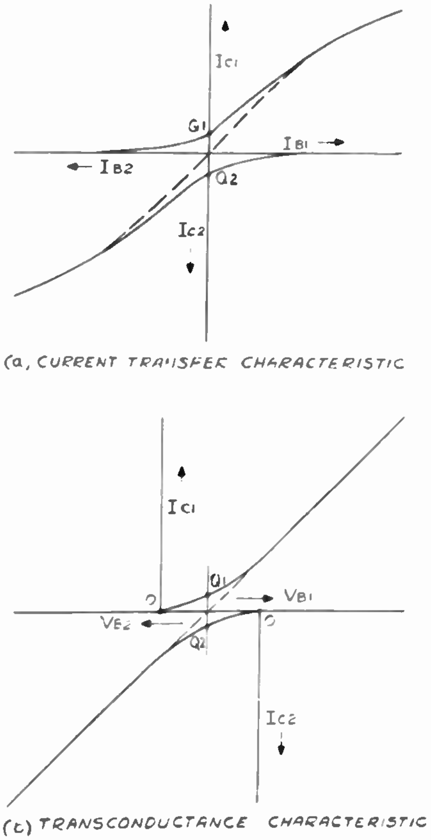

Fig. 20—Transfer characteristics for common emitter Class B push-pull operation.

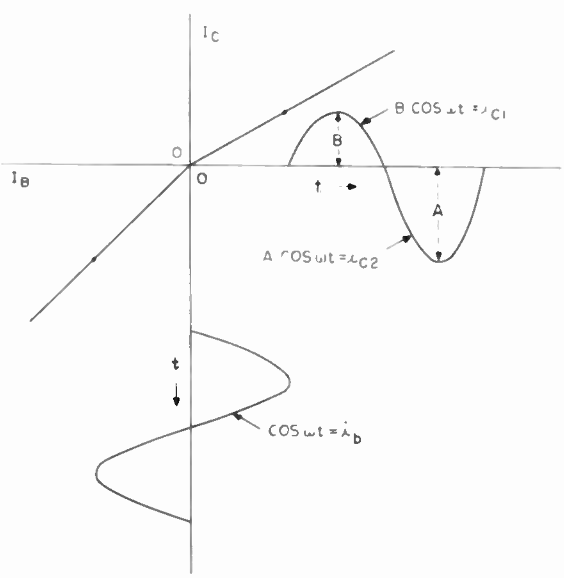

Fig. 21—Composite push-pull Class B transfer characteristic—effect of gain difference.

supply regulation is poor the collector bias point will vary with signal level. This variation may affect the linearity of the transfer characteristic.

Distortion caused by the use of two transistors having different gains is illustrated in Fig. 21 which shows a common emitter composite current transfer characteristic. The approximation that each transistor has a linear characteristic is used to facilitate the analysis. The output current waveform for a sinusoidal input current is shown. If each transistor is assumed to have unity peak input current then the current gain of one transistor is A and that of the other is B. Fourier analysis shows the collector current to be:

$$i_c = \frac{A-B}{\pi} + \frac{A+B}{2}\cos\omega t + \frac{A-B}{\pi}\sum_{n}^{\infty}\left[\frac{(-1)^{n/2}}{n+1} + \frac{(-1)^{n/2+1}}{n-1}\right]\cos n\omega t, \quad (39)$$

where $n=2p$ and p is integer. The ratio of the nth harmonic to the fundamental is

$$R_n = \left|\frac{2}{\pi}\,\frac{A-B}{A+B}\left[\frac{(-1)^{n/2}}{n+1} + \frac{(-1)^{n/2+1}}{n-1}\right]\right|. \quad (40)$$

A plot of the quantity $|A-B|/|A+B|$ versus A/B, the ratio of the transistor current gains, is shown in Fig. 22.

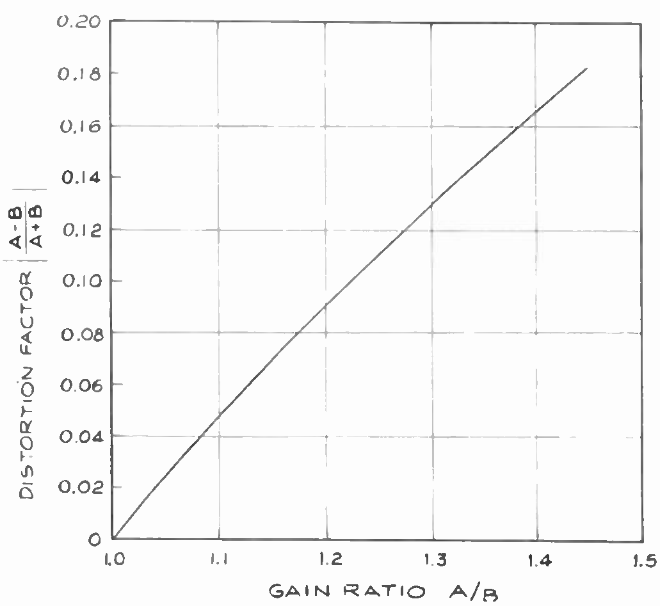

Fig. 22—Distortion factor vs gain ratio.

Improper biasing may produce two different effects depending on the direction of bias. Forward bias results in Class AB operation of the transistors. This type of operation will eliminate nonlinearities at the crossover portion of the transfer characteristic but may introduce severe nonlinearities at higher values of collector current. The efficiency of operation is also decreased. Fig. 23 illustrates the effect of excessive reverse bias on the composite transfer characteristic. Operation of this type results in distortion known as "join-up," "crossover," or "class B" distortion. For the purpose of analysis the transfer characteristics of both transistors are assumed to be identical and linear.

If the constant K is the reciprocal of the current gain and ϕ is one-half the "crossover" angle then for unit input current the output current may be shown to be:

$$Ki_c = \frac{1}{\pi}\left[(\pi - 2\phi) + \sin 2\phi - 4\sin\phi\cos\phi\right]\sin\omega t$$
$$+ \sum_n^{\infty} \frac{4}{\pi}\left[\frac{1}{n(n^2-1)}\sin\phi\cos\phi - \frac{n}{n^2-1}\sin\phi\cos\phi\right]\sin n\omega t, \quad (41)$$

where $n = 2p+1$ and p is integer.

For small values of "crossover" angle such that

$$\sin\phi \cong \phi$$

the equation for collector current reduces to:

$$Ki_c \cong \frac{1}{\pi}\left[\pi - 4\phi\right]\sin\omega t + \sum_n^{\infty} \frac{4}{\pi}\left[\frac{n\sin n\phi}{n^2-1}\right]\sin n\omega t. \quad (42)$$

The ratio of the nth harmonic to the fundamental is:

$$R_n \cong \frac{4\left[\frac{n\sin n\phi}{n^2-1}\right]}{\pi - 4\phi}. \quad (43)$$

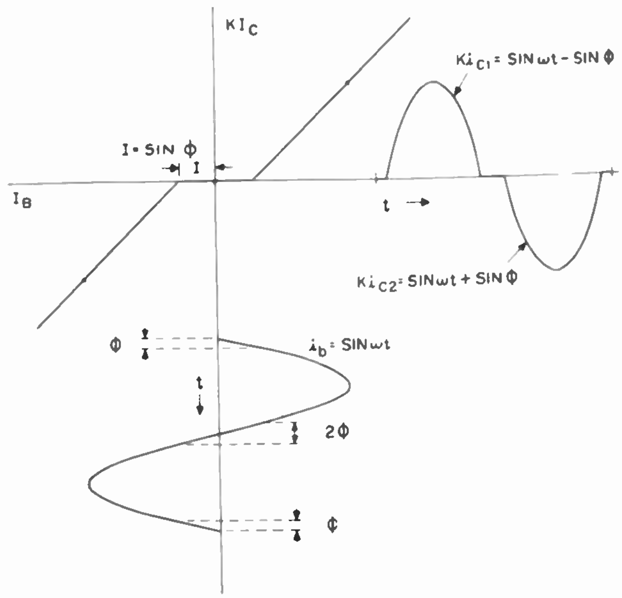

Fig. 23—Composite push-pull Class B transfer characteristic—effect of improper bias.

A plot showing the fundamental frequency and third harmonic as a function of crossover angle is shown in Fig. 24. Substitution in (43) shows that the fifth and seventh harmonics approach the magnitude of the third harmonic at small "crossover" angles.

When an input transformer is not used to drive a push-pull Class B output stage the preceding stage is usually a phase inverter which is RC or LC coupled to the output stage. The "on," "off" action of a single transistor of the push-pull combination produces a reverse bias on the stage. This bias is a function of the

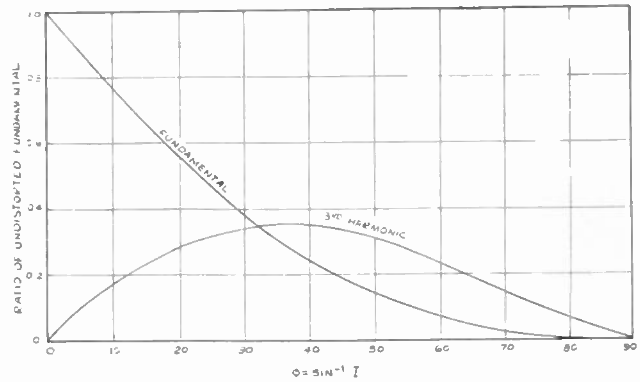

Fig. 24—Amplifier output vs crossover angle.

input signal amplitude and may cause serious crossover distortion. Class AB operation will compensate for this effect but only at the expense of a reduction in the efficiency of the output stage. Fig. 25 shows the diagram of a push-pull common emitter circuit which eliminates this effect. The diodes D_1 and D_2 effectively short out the signal induced bias. The diode arrangement may be employed in conjunction with an input bias supply when necessary.

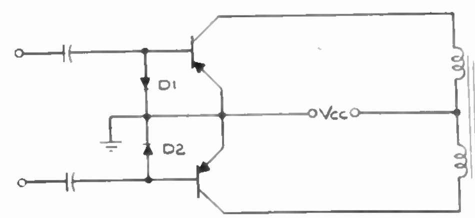

Fig. 25—Class B push-pull amplifier.

Driver Stages

For many transistor output stages the required ac input power is sufficiently large to necessitate the use of a driver stage which is itself a power amplifier. When transformer coupling is employed between driver and output stage the driver may be designed using standard power amplifier design techniques. In addition, an interstage transformer provides the necessary phase inversion to drive a push-pull stage. If an interstage transformer is not employed, the driver must not only supply the necessary driving power but also perform the function of phase inversion.

Fig. 26 shows the circuit diagram of a split load phase inverter employing a single transistor. The transistor is normally biased for Class A operation. For linear operation this stage must be supplied from a high impedance source when driving a nonlinear load such as the input impedance of a Class B push-pull output stage. This is necessary since any variation of the emitter load impedance appears [increased by the factor $(1/1-\alpha)$] in the input impedance of the stage.

The emitter loading effect is eliminated by the use of a two transistor phase inverter such as that shown in

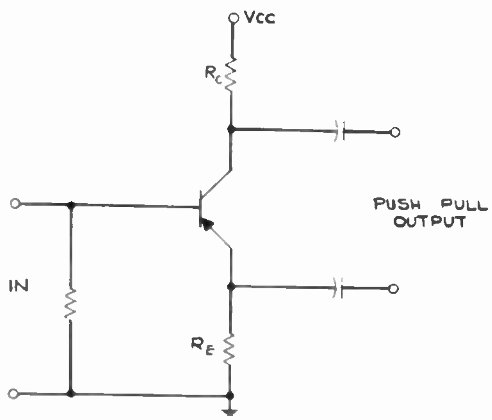

Fig. 26—Split load phase inverter.

Fig. 27. This circuit requires the use of transistors which have a relatively high cutoff frequency since the output signal from transistor $Q2$ must pass through both transistors. Assuming the transistors $Q1$ and $Q2$ are identical in all respects and the signal undergoes no phase change, the outputs will be equal and 180° out of phase when

$$R_S \cong \frac{\alpha}{1-\alpha} R_{IN} \tag{44}$$

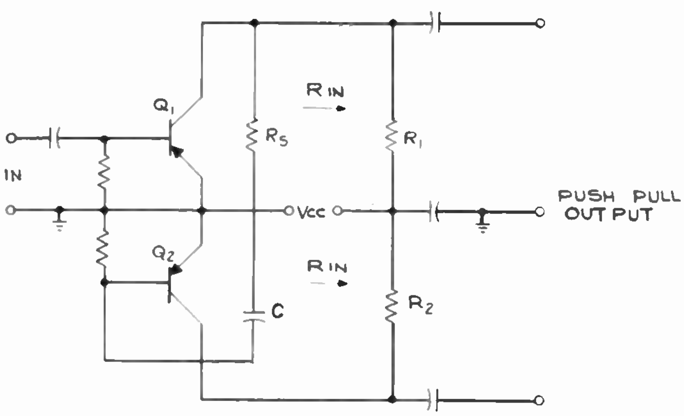

Fig. 27—Two transistor phase inverter.

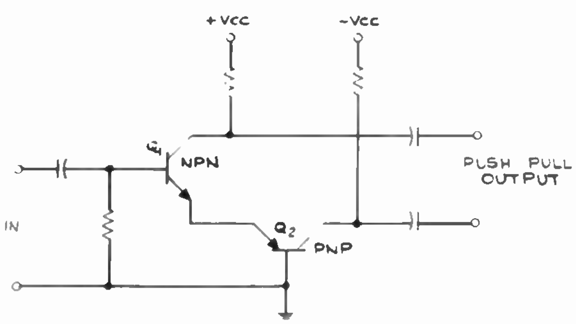

Fig. 28—Complementary phase inverter.

if $R_{IN} \ll R_S$ and C is large. Fig. 28 shows the circuit diagram of a phase inverter stage which eliminates the phase problem encountered in circuits like that shown in Fig. 27. The common base stage $Q2$ introduces negligible phase change at audio frequencies. The requirement for equal outputs differing in phase by 180° is that the short circuit current gains of the two transistors be equal.

Complementary Symmetry Operation

The fact that there are two basic types of junction transistors—*n-p-n* and *p-n-p*—allows a freedom of circuit design which is impossible with electron tubes [6]. Fig. 29 shows a circuit diagram of a circuit which makes use of the complementary properties of transistors. Circuits of this general type may be employed successfully as power amplifiers for audio frequency output stages. The circuit is particularly desirable because it provides push-pull performance while requiring no phase inversion from the driver.

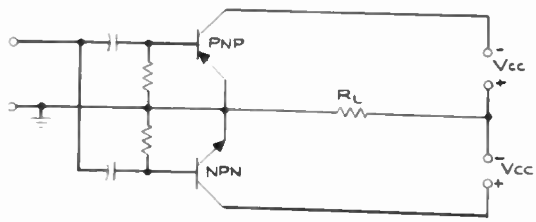

Fig. 29—Complementary symmetry stage.

A signal impressed at the input will increase the collector current of one transistor and decrease the collector current of the other. The difference in the two currents flows through the load resistance. Optimum operation requires that the transistors be complementary in their transfer properties. When this condition is satisfied no direct current flows in the load. The transistors may be biased Class A, Class AB or Class B. The maximum output power is:

$$\text{O.P.} = \frac{V_{cc}^2}{2R_L}. \tag{45}$$

The unique complementary properties of transistors have many useful applications. Alternate types may be cascaded to form direct coupled amplifiers. Combinations such as direct coupling with complementary push-pull stages allow a latitude of circuit design previously unavailable with electron tubes.

Appendix I

Derivation of Input Characteristic Equation

The total current across a $p-n$ junction for any applied voltage V is given by

$$I = I_S\left(\exp\frac{qV}{kT} - 1\right), \tag{46}$$

where:

I_S = The saturation current due to spontaneous minority carrier generation on both sides of the junction.

V = The voltage impressed across the junction.

k = Boltzman's constant.

T = Temperature in °K.

Consider the transistor shown in Fig. 30. When the interaction effects of collector voltage are neglected the emitter current may be written [7]:

$$I_E = I_{ES}\left(\exp \frac{qV_{EB}}{kT} - 1\right), \tag{47}$$

where:

I_{ES} = the emitter saturation current
V_{EB} = the emitter to base voltage.

Solving (47) for V_{EB}

$$V_{EB} = \frac{kT}{q} \ln \frac{I_E + I_{ES}}{I_{ES}}. \tag{48}$$

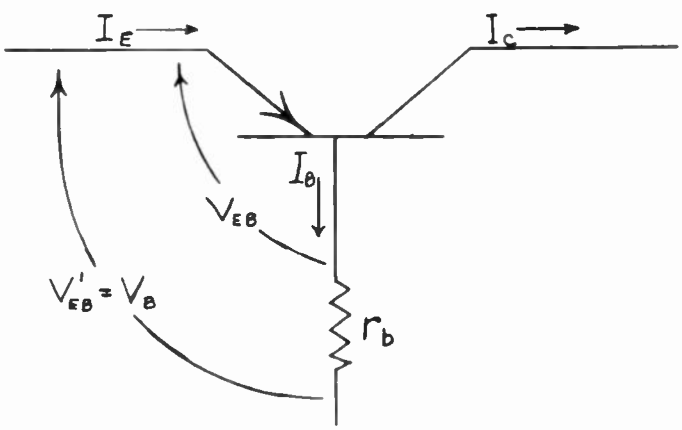

Fig. 30

Since $I_E \gg I_{ES}$ over the range of operation

$$V_{EB} \cong \frac{kT}{q} \ln \frac{I_E}{I_{ES}}. \tag{49}$$

The direct current in the emitter is related to the direct current in the base by

$$I_E \cong \frac{I_B}{1 - \alpha'}. \tag{50}$$

where α' is defined as: $\alpha' = I_C/I_E$ the dc current gain. Substituting (50) in (49)

$$V_{EB} \cong \frac{kT}{q} \ln \frac{I_B}{(1 - \alpha')I_{ES}}. \tag{51}$$

With the base resistance r_b in series with the base, the voltage V_{EB}' across resistance and junction becomes

$$V_{EB}' \cong I_B r_b + \frac{kT}{q} \ln \frac{I_B}{(1 - \alpha')I_{ES}}. \tag{52}$$

Eq. (52) can be written in terms of the base voltage of the transistor where $V_{EB}' = V_B$

$$V_B \cong I_B r_b + \frac{kT}{q} \ln \frac{I_B}{(1 - \alpha')I_{ES}}. \tag{53}$$

Eq. (53) is the common emitter input characteristic equation. If two points on the input characteristic are known the values of the emitter saturation current and the base resistance of the transistor can be obtained. The input resistance can be found from the slope of the input characteristic.

$$R_{IN} = \frac{dV_B}{dI_B} \cong r_b + \frac{kT}{qI_B}, \tag{54}$$

where α' is considered constant.
Substituting (50) in (54)

$$R_{IN} \cong r_b + \frac{kT}{qI_E(1 - \alpha')}. \tag{55}$$

Using the relationship [1]:

$$\frac{kT}{qI_E} = r_e, \tag{56}$$

the input resistance is

$$R_{IN} \cong r_b + \frac{r_e}{1 - \alpha'}. \tag{57}$$

The value of R_{IN} is seen to be approximately equal to the common emitter short-circuit input impedance h_{11}. This is in agreement with measured results and is due to the fact that, in most applications of transistors as power amplifiers $R_L \ll r_{22}$.

Appendix II

Taylor Series Analysis of Class A Operation

Consider the circuit design shown in Fig. 31. The common emitter collector current (I_C) can be expressed as a function of base current (I_B) and collector voltage (V_C).

$$I_C = f(I_B, V_C). \tag{58}$$

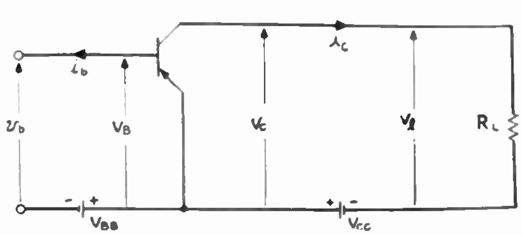

Fig. 31—Common emitter Class A power amplifier stage.

The collector current may be expressed in the form of a power series about an operating point $(I_B, V_C)_Q$

$$I_C = f(I_B, V_C)_Q + \frac{\partial I_C}{\partial I_B} dI_B + \frac{\partial I_C}{\partial V_C} dV_C + \frac{1}{2}\frac{\partial^2 I_C}{\partial I_B^2}(dI_B)^2 + \frac{\partial^2 I_C}{\partial I_B \partial V_C} dI_B dV_C + \frac{1}{2}\frac{\partial^2 I_C}{\partial V_C^2}(dV_C)^2 + \cdots. \tag{59}$$

Excursions about the operating point are defined as

$$I_C - I_{CQ} = dI_C = i_c,$$

where

$$I_{CQ} = f(I_B, V_C)_Q$$
$$dI_B = i_b$$
$$dV_C = v_c$$

The partial derivatives are evaluated at the operating point I_{CQ} and are identified as:

$$\frac{\partial I_C}{\partial I_B} = h_{21}$$
$$\frac{\partial I_C}{\partial V_C} = h_{22}.$$

Eq. (59) may now be written in the form

$$i_c = h_{21}i_b + h_{22}v_c + \frac{1}{2}\frac{\partial h_{21}}{\partial I_B}i_b^2 + \frac{\partial h_{21}}{\partial V_C}i_bv_c + \frac{1}{2}\frac{\partial h_{22}}{\partial V_C}v_c^2 + \cdots. \quad (60)$$

The common emitter base current (I_B) may be expressed as a function of base voltage (V_B) and collector voltage (V_C)

$$I_B = f(V_B, V_C). \quad (61)$$

In a manner similar to the collector current expansion the base current may be expanded about an operating point $f(V_B, V_C)_Q$ as follows:

$$i_b = g_{11}v_b + g_{12}v_c + \frac{1}{2}\frac{\partial g_{11}}{\partial V_B}v_b^2 + \frac{\partial g_{11}}{\partial V_C}v_bv_c + \frac{1}{2}\frac{\partial g_{12}}{\partial V_C}v_c^2 + \cdots, \quad (62)$$

where

$$g_{11} = \frac{\partial I_B}{\partial V_B}$$
$$g_{12} = \frac{\partial I_B}{\partial V_C}$$

evaluated at the operating point.

In the region of operation with which we are concerned the contribution to collector current (I_C) and base current (I_B) in (60) and (62) respectively of terms of higher order than the second may be considered small. Terms of higher order than the second are, therefore, neglected for the purpose of this analysis.

Further simplification is possible in the case of transistors employed as power amplifiers. Certain terms in the second-order expansions may be considered negligible. It is necessary to refer to the transistor characteristics at this point to determine which terms may be dropped. Considerations discussed in the second section indicate that the following terms may be considered negligible in the base current expansion for many transistors:

$$g_{12}v_c, \qquad \frac{\partial g_{11}}{\partial V_C}v_bv_c, \qquad \frac{1}{2}\frac{\partial g_{12}}{\partial V_C}v_c^2.$$

In the collector current expansion the following two assumptions are made:

1. The change in the current amplification of the device with collector voltage is negligible so that $\partial h_{21}/\partial V_C$ is small.

2. The output characteristics of the device, over the range of operation, are sufficiently linear so that $\partial h_{22}/\partial V_C$ is small.

The following terms are considered negligible in the collector current expansion:

$$\frac{\partial h_{21}}{\partial V_C}i_bv_c, \qquad \frac{1}{2}\frac{\partial h_{22}}{\partial V_C}v_c^2.$$

The expression for the base current reduces to:

$$i_b \cong g_{11}v_b + \frac{1}{2}\frac{\partial g_{11}}{\partial V_B}v_b^2. \quad (63)$$

By the substitution $v_c = -i_cR_L$ the expression for the collector current becomes:

$$i_c \cong \frac{h_{21}}{K_1}i_b + \frac{1}{2K_1}\frac{\partial h_{21}}{\partial I_B}i_b^2, \quad (64)$$

where

$$K_1 = 1 + R_L/r_{22}.$$

By similar approximations the collector current may be expressed as a function of base voltage and collector voltage as follows:

$$i_c \cong g_{21}v_b + \frac{1}{2}\frac{\partial g_{21}}{\partial V_B}v_b^2 + g_{22}v_c \quad (65)$$

and the base voltage may be expressed as:

$$v_b \cong h_{11}i_b + \frac{1}{2}\frac{\partial h_{11}}{\partial I_B}i_b^2. \quad (66)$$

Eq. (65), may be expressed in the same form as (64)

$$i_c \cong \frac{g_{21}}{K_2}v_b + \frac{1}{2K_2}\frac{\partial g_{21}}{\partial V_B}v_b^2, \quad (67)$$

where

$$K_2 = 1 + g_{22}R_L.$$

Appendix III

Output Stage Transistor Performance in Terms of the Small Signal "h" Parameters

Consider the circuit shown in Fig. 32 where "A" represents the transistor. The circuit may be described in terms of the small signal "h" parameters:

$$v_g = (R_G + h_{11})i_1 + h_{12}v_2 \quad (68)$$
$$i_2 = h_{21}i_1 + h_{22}v_2, \quad (69)$$

where

$$i_2 = ki_1$$

$$v_2 = v_l = -i_2R_L = -ki_1R_L$$

$$k = \text{operating current gain.}$$

The operating current gain [from (69)] is

$$k = \frac{h_{21}}{1 + h_{22}R_L}$$

The input resistance [substitution for V_2 in (68)] is:

$$R_{IN} = h_{11} - \frac{h_{12}h_{21}R_L}{1 + h_{22}R_L}.$$

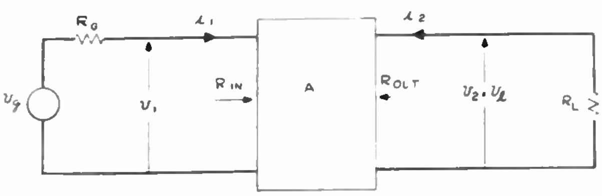

Fig. 32—Output stage ac circuit.

The output resistance [Solving (68) for i_1 when $v_g = 0$ and substituting for i_1 in (69)] is

$$R_{OUT} = \frac{R_G + h_{11}}{h_{22}(R_G + h_{11}) - h_{12}h_{21}}.$$

The operating power gain or transducer gain is defined:

$$TG = \frac{4R_G}{R_L}\left[\frac{v_l}{v_g}\right]^2$$

$$TG = \frac{4R_GR_Lh_{21}^2}{[(R_G + h_{11})(1 + h_{22}R_L) - h_{12}h_{21}R_L]^2}.$$

When the transistor "*A*" in Fig. 32 represents the output stage transistor the approximate values of the "*h*" parameters are shown in Table I below, where the following assumptions are made:

$$r_b \ll r_c \quad \text{and} \quad r_e \ll r_c(1 - \alpha).$$

TABLE I

	Common Base	Common Emitter	Common Collector
h_{11}	$r_e+(1-\alpha)r_b$	$r_b+\frac{r_e}{1-\alpha}$	$r_b+\frac{r_e}{1-\alpha}$
h_{12}	0	0	1
h_{21}	$-\alpha$	$\frac{\alpha}{1-\alpha}$	$\frac{-1}{1-\alpha}$
h_{22}	$\frac{1}{r_c}$	$\frac{1}{r_c(1-\alpha)}$	$\frac{1}{r_c(1-\alpha)}$

The properties of the circuit, Fig. 32, in terms of the transistor α and r's are shown in Table II below, where the following assumptions are made in addition to those mentioned above:

$$R_L \ll r_c(1 - \alpha)$$

$$R_G \gg r_b + \frac{r_e}{1 - \alpha}$$

$$r_e \ll (1 - \alpha)r_b \ll R_L, \qquad \text{(for high-power applications).}$$

TABLE II

	Common Base	Common Emitter	Common Collector
R_{IN}	$r_e+(1-\alpha)r_b$	$r_b+\frac{r_e}{1-\alpha}$	$r_b+\frac{r_e+R_L}{1-\alpha}$
R_{OUT}	r_c	$r_c(1-\alpha)$	$\frac{r_eR_G(1-\alpha)}{r_e+R_G}$
Transducer Gain	$\frac{4R_GR_L\alpha^2}{[R_G+r_e+(1-\alpha)r_b]^2}$	$\frac{4R_GR_L\alpha^2}{[r_e+(1-\alpha)(R_G+r_b)]^2}$	$\frac{4R_GR_L}{[R_L+r_e+(1-\alpha)(R_G+r_b)]^2}$
Maximum Available Power Gain	$\frac{\alpha^2R_L}{R_G}$	$\left[\frac{\alpha}{1-\alpha}\right]^2\frac{R_L}{R_G}$	$\frac{1}{(1-\alpha)^2}\,\frac{R_L}{R_G}$
Power Gain	$\frac{\alpha^2R_L}{r_e+(1-\alpha)r_b}$	$\frac{\alpha^2}{1-\alpha}\,\frac{R_L}{r_e+(1-\alpha)r_b}$	$\frac{1}{(1-\alpha)}\,\frac{R_L}{R_L+r_e+(1-\alpha)r_b}$
Power Gain (High Power)	$\frac{\alpha^2}{1-\alpha}\,\frac{R_L}{r_b}$	$\frac{\alpha^2}{(1-\alpha)^2}\,\frac{R_L}{r_b}$	$\frac{1}{1-\alpha}$

Appendix IV

Common Emitter Class A Push-Pull Operation

The ac circuit diagram of a push-pull Class A common emitter stage is shown in Fig. 33(a). When the stage is driven by a constant current source the approximate equivalent circuit at the output is shown in Fig. 33(b).

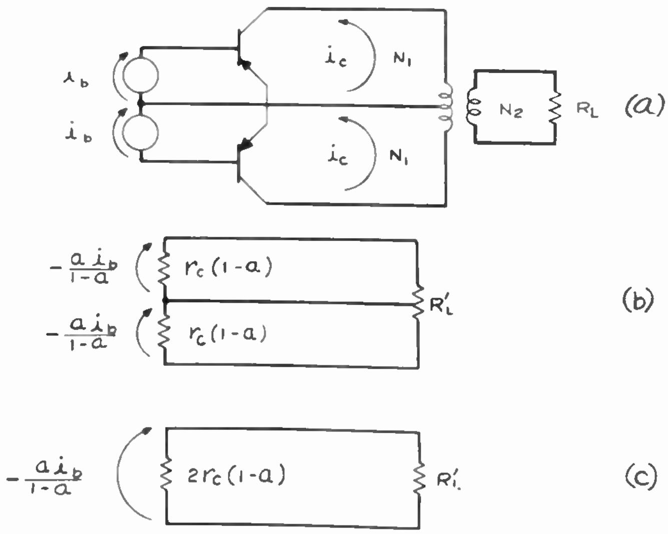

Fig. 33—Class A push-pull operation.

Where

$$R_L' = \left[\frac{2N_1}{N_2}\right]^2 R_L. \qquad (70)$$

The equivalent circuit in Fig. 33(b) may be reduced to that shown in Fig. 33(c).

The output power of the push-pull circuit can be shown to be:

$$P_p = \left[\frac{\frac{r_c(1-\alpha)}{2}\left(\frac{-2\alpha i_b}{1-\alpha}\right)}{\frac{r_c(1-\alpha)}{2}+\frac{R_L'}{4}}\right]^2 \frac{R_L'}{4}. \qquad (71)$$

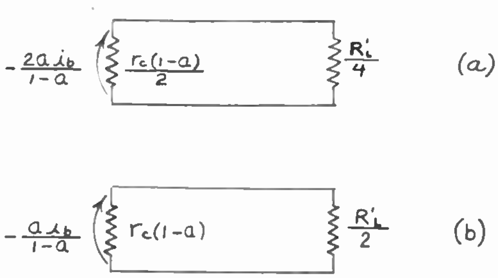

Fig. 34—Push-pull and single-ended equivalent output circuits.

From (71) it is seen that the output equivalent circuit may be drawn as shown in Fig. 34 (a).

The push-pull common emitter Class A stage may be represented as a single equivalent transistor which has an output resistance $r_c(1-\alpha)/2$, a current gain $2\alpha/(1-\alpha)$ and drives a load resistance which is one-fourth the collector-to-collector load resistance (R_L').

The output equivalent circuit of one transistor of the push-pull pair is shown in Fig. 34(b). The output power of one transistor is half the total power:

$$P_s = \frac{P_p}{2} = \left[\frac{r_c(1-\alpha)\left(\frac{-\alpha i_b}{1-\alpha}\right)}{r_c(1-\alpha)+\frac{R_L'}{2}}\right]^2 \frac{R_L'}{2}. \qquad (72)$$

Thus, from (72) the single transistor drives a load which is one-half the collector-to-collector load resistance. The operation of the push-pull stage is shown in Fig. 15 where the load line $R_L'/4$ is shown as determining the operating path of the push-pull equivalent transistor. The slope of the composite output characteristic is seen to be half that of a single unit. The lines O_1 and O_2 show the operating paths of the transistors taken separately. These lines (neglecting nonlinearity) show that each transistor effectively drives a load $R_L'/2$.

When the push-pull stage is driven from a high impedance source the loading conditions for maximum power gain are:

$$\frac{R_L'}{4} = \frac{r_c(1-\alpha)}{2}. \qquad (73)$$

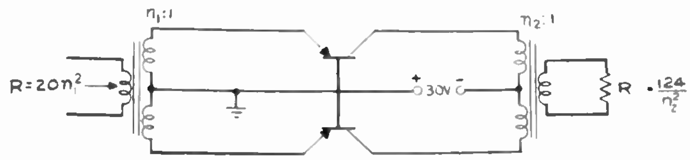

Fig. 35—Class B push-pull output stage.

The input resistance (R_{IN_p}) of the push-pull stage is twice the input resistance (R_{IN}) of a single transistor

$$R_{IN_p} = 2R_{IN}. \qquad (74)$$

When driven from a high impedance source the matched output gain from a push-pull Class A common emitter stage is:

$$G = \left(\frac{\alpha}{1-\alpha}\right)^2 \frac{R_L'}{8R_{IN}}. \qquad (75)$$

Appendix V

Design of a Class B, Push-Pull, Common Base Output Stage

This is a design of a common base push-pull Class B audio frequency power amplifier using 2-watt *p-n-p* fused alloy germanium power transistors. The following information is established from the transistor characteristics.

Maximum Collector Voltage	$V_{c\,max}=$	60 volts
Base resistance	$r_b=$	100 ohms
Collector resistance	$r_c=$	20,000 ohms
Short-circuit current gain	$\alpha=$	0.95
Collector leakage current	$I_{co}=$	100 μA.

The necessary information for the design of the amplifier is contained in the fourth section. The circuit diagram is shown in Fig. 35.

Referring to Fig. 18

$$V = \frac{V_{max}}{2} = 30 \text{ volts.}$$

From (34), assuming I_{co} negligibly small

$$I \cong \frac{29.2}{30} = 970 \text{ ma.}$$

From (27)

$$R_L = \frac{V}{I} = 31 \text{ ohms.}$$

The input resistance, assuming r_e negligibly small

$$R_{IN} \cong r_b(1 - \alpha) = 5 \text{ ohms.}$$

The operating current gain

$$A = \frac{h_{21}}{1 + h_{22}R_L} \cong \frac{\alpha}{1 + \frac{R_L}{r_c}} \cong 0.95$$

since

$$\frac{R_L}{r_c} \ll 1.$$

The power gain of the stage from (38)

$$PG = A^2 \frac{R_L}{R_{IN}} \cong 0.9 \times \frac{31}{5} \cong 5.6$$

If we assume the stage is transformer coupled at the input and the output by ideal transformers then the resistance across the input transformer secondary is 20 ohms and the resistance across the primary of the output transformer is 124 ohms. For some transistors, it may be necessary to supply a small forward bias to the input circuit. This biasing voltage is usually connected between ground and the center tap of the input transformer secondary. Since leakage current is very small compared to the total current swing the efficiency of this amplifier at maximum output approaches the theoretical upper limit for Class B operation.

$$\eta \cong 78 \text{ per cent.}$$

The maximum ac output power of this amplifier is 14.5 watts. This requires an input power of 2.6 watts.

Where high efficiency and optimum linearity are required common base stages are used. However, in the example above the use of a common emitter connection may be indicated because of its higher power gain. The common emitter power gain in this application is approximately (from Appendix III)

$$PG \cong 106.$$

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D. R. Fewer

A native of New Brunswick, Canada, where he was born on March 12, 1923, Mr. Fewer was a radar officer in the Royal Canadian Air Force, serving in Canada, the Middle East, Italy, the United Kingdom, and Germany from 1941–46. He was graduated in 1950 from the University of New Brunswick with the B.Sc. degree in mathematics and physics. From 1951–52 he was a Research Fellow at the University of Western Ontario, conducting research for the U. S. Air Force Geophysics Research Division. He was awarded the M.Sc. degree in physics in 1952 and then joined the staff of Bell Laboratories.

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M. Camras (S'41–A'42–SM'48–F'52) was born in Chicago, Ill. He received the B.Sc. degree in electrical engineering from Armour Institute of Technology in 1940, and the M.Sc. degree from Illinois Institute of Technology in 1942.

Mr. Camras in the last ten years, as staff member of Armour Research Foundation, has done considerable work in magnetic recording. Some developments which he was connected with are: stainless steel recording media, supersonic bias, improved recording heads, high-coercive coated tapes, magnetic sound on film, stereophonic magnetic recording, and magnetic duplicating by contact printing.

Marvin Camras

In addition to his IRE membership, he is a member of Sigma Xi, Tau Beta Pi, and Eta Kappa Nu.

IRE Professional Group on Audio Combined Index for 1955

Use of the Index

The combined indexes which follow are of three types. The first type is simply a compilation of Tables of Contents of TRANSACTIONS OF THE IRE-PGA and the Audio portion of the CONVENTION RECORD. Next is an Author Index. The third type is an Analytic Subject Index.

The volume system of indexing began with the first issue of 1953. Volume AU-3, issues 1, 2 . . . 6, contain all IRE-PGA publications for the year 1955 and the Audio part of Section 7 of the 1955 CONVENTION RECORD. In the Tables of Contents, this section is numbered CR-3-7, and inserted chronologically between issues AU-3-4 and AU-3-5, TRANSACTIONS OF THE IRE-PGA.

In both the Author Index and the Analytic Subject Index references are made to publications by the issue and page number in the volume (*e.g.*, AU-3-4, 104).

The Analytic Subject Index lists titles under the appropriate classifications in the series shown below. In many cases valuable material is published under titles which cannot be fully descriptive of all the material which the paper covers. It is for this reason that some titles are listed under various classifications, some of which may seem inappropriate to the title itself. It is hoped that this will increase the probability of finding quickly most of the information available under a particular classification.

Classification of Subjects

1. IRE-PGA
   - 1.1 General
   - 1.2 Constitution and By-Laws
   - 1.3 National and Regional Meetings
   - 1.4 Chapters
   - 1.5 Membership
   - 1.6 Transactions
   - 1.7 People
2. Bibliographies, Reviews, Standards, Tapescripts
   - 2.1 Bibliographies
   - 2.2 Reviews
   - 2.3 Standards
   - 2.4 Tapescripts
3. Sound Systems
   - 3.1 General
4. Microphones
   - 4.1 General
   - 4.2 Condenser
   - 4.3 Magnetic
   - 4.4 Crystal
   - 4.5 Moving—Coil
   - 4.6 Ribbon
   - 4.9 Special Microphones
5. Amplifiers
   - 5.1 General
   - 5.2 Preamplifiers and Voltage Amplifiers
   - 5.3 Power Amplifiers
   - 5.4 Frequency-Range Dividing Networks
   - 5.9 Special Amplifiers
6. Loudspeakers
   - 6.1 General
   - 6.2 Direct-Radiator Units
   - 6.3 Horn-Driver Units
   - 6.4 Horns, Enclosures, Baffles
   - 6.9 Special Types
7. Disc Recording and Reproduction
   - 7.1 General
   - 7.2 Discs
   - 7.3 Recording
   - 7.4 Pickups and Tone Arms
   - 7.5 Pre-emphasis and Postequalization
   - 7.9 Special Mechanical Recorders
8. Magnetic Recording and Reproduction
   - 8.1 General
   - 8.2 Tape and Wire
   - 8.3 Recording and Erasing
   - 8.4 Playback
   - 8.5 Pre-emphasis and Postequalization
   - 8.9 Special Magnetic Recorders
9. Acoustics
   - 9.1 General
   - 9.2 Room Acoustics
   - 9.3 Sound Waves and Vibrations
   - 9.4 Speech
   - 9.5 Music
   - 9.6 Hearing
10. Broadcast Audio
11. Audio Measuring Equipment and Techniques
12. Electronic Musical Instruments

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AUTHOR INDEX FOR 1955 IRE-PGA PUBLICATIONS

ANALYTIC SUBJECT INDEX FOR 1955 IRE-PGA PUBLICATIONS

INSTITUTIONAL LISTINGS

ALLIED RADIO, 833 West Jackson Blvd., Chicago 7, Illinois
Everything in Radio, Television, and Industrial Electronics. .
(J. W. Rubin)

ALTEC LANSING CORPORATION, 9356 Santa Monica Blvd., Beverly Hills, California
Microphones, Speakers, Amplifiers, Transformers, Speech Input
(A. A. Ward)

AMPEX CORPORATION, 934 Charter St., Redwood City, California
Magnetic Tape Recoders for Audio and Test Data
(H. Johnston)

AMPLIFIER CORPORATION OF AMERICA, 398 Broadway, New York 13, New York
Battery-Operated Magnetic Tape Recorders, Amplifiers, Power Suppliers
(Harold Wallerstein)

AUDIOPHILE RECORDS, Saukville, Wisconsin
High Quality Disc Recordings for Wide Range Equipment
(E. D. Nuun)

BALLANTINE LABORATORIES, INC., Fanny Rd., Boonton, New Jersey
Electronic, Voltmeters, Decade Amplifiers, Voltage Calibrators, Multipliers, Shunts
(F. R. Zayac)

CINEMA ENGINEERING CO., Division Aerovox Corp., 1100 Chestnut St., Burbank, California
Equalizers, Attenuators, Communication Equipment
(James L. Fouch)

THE DAVEN COMPANY, 191 Central Ave., Newark 4, New Jersey
Attenuators, Potentiometers, Resistors, Rotary Switches, Test Equipment
(S. Morehouse)

ELECTRO-VOICE, INC., Buchanan, Michigan
Microphones, Pickups, Speakers, Television Boosters, Acoustic Devices
(A. M. Wiggins)

GENERAL CERAMICS CORPORATION, Keasbey, New Jersey
Technical Ceramics—Steatites and Aluminum, Ferramics, Solderseals
(Frederick F. Sylvester)

INSTITUTIONAL LISTINGS (Continued)