

elements of
TAPE
RECORDER
CIRCUITS

Herman Burstein • Henry C. Pollak

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RECORDER
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herman burstein and henry c. pollak



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introduction

THIS book is intended for the audiophile as well as the technician interested in the tape recorder; for the audiophile who wants to know "what makes it tick" and for the technician who wishes to approach a tape recorder not only with instruments and a schematic but also with a secure understanding. Comprehension of the factors that enter into the design and operation of a tape machine enables a purchaser to select wisely from the available units and to obtain the best possible recording results; it enables the service technician to insure that a tape recorder yields the performance designed into it.

It is assumed that the reader has an elementary knowledge of electronics and audio such as may be readily acquired from some of the popular and readily assimilable books on the market.¹ If he has a rudimentary understanding of electricity and magnetism, of audio terminology and the fundamental building blocks of electronic circuits—resistors, capacitors, inductors, vacuum tubes and transformers—he is equipped to follow the discussion. Even the reader who lacks this background should find much that gives him a clearer picture of what is underneath the surface of tape recorders.

In substantial part, the book is written from the design viewpoint. It should be quickly added that this is not a text for designers of tape recorders. Rather, it seeks to explain circuitry in

¹ John T. Frye, *Basic Radio Course*; Donald Carl Hoefler, *Basic Audio Course*, (Gernsback Library, Inc.); David Fidelman, *Guide to Audio Reproduction*, (John F. Rider Publisher, Inc.).

terms of what the designer is trying to accomplish. To the extent that circuits are analyzed in certain chapters, the purpose is not an exercise in circuit analysis but to uncover fundamental principles. A grasp of principles will equip the reader to understand many more circuits than these pages hold room for.

To understand the tape recorder it is not enough to comprehend the basic ideas at work. It is necessary to examine the problems that have led to their evolution. The problems remain latent and rise to plague the user or technician when the tape recorder malfunctions because of wear, misalignment, abuse, etc. Stated differently, it is desirable to know not only what makes a tape recorder work satisfactorily but also what makes it work unsatisfactorily.

Side by side with electronic problems there is the ever-present question of cost. Economy generally dictates the course that the designer must follow. A given electronic problem may have several solutions with varying degrees of merit, but cost may prevent the designer from using that which he considers best. Here, then, is one of the most important factors accounting for substantial differences among tape recorders. In a rough way, one may differentiate between "moderate-price" tape recorders on the one hand, selling for less than \$300, and professional and semi-professional units on the other hand, priced from \$300. The following chapters attempt to give due space to each class of recorder. As a means of directing attention to good practice, the discussion is likely to focus somewhat more on the circuits and principles exemplified in the better units.

An appreciation of tape recorder problems, principles and practices is not a matter of mere academic interest. There are very practical advantages to such knowledge. The reader can expect this knowledge to serve him well in extracting the best possible performance from his machine. Moreover, many a technically minded audio hobbyist eventually becomes concerned with the design viewpoint when he finds himself dissatisfied with some function, circuit or facility of his recorder and wishes to improve upon it, possibly to the extent of rebuilding a substantial portion. Here one may draw a parallel with the extensive alterations which audiophiles perform upon such equipment as audio amplifiers and preamplifiers. Numerous articles have been written on changes intended to improve the performance of these units. As the audiophile grows more at home with the tape recorder, he may similarly wish to try his hand at improving its performance.

In the interest of maximum clarity, mathematics will be

avoided as an explanatory device, with very few exceptions where no more than elementary arithmetic is used to make an important point clear. In most instances, the discussion can be offered in commonsense terms. Where only mathematics of a fairly high level can prove a point, the reader's acceptance of an unproven statement will have to rest upon his confidence in the authors.

The terms amplifier, tape amplifier, record amplifier and playback amplifier will appear frequently.² To avoid possible misunderstanding, it should be made clear at the outset that these do not include the audio *power* amplifier often found in tape recorders, particularly in moderate-price machines. Explicit use will be made of the phrase "power amplifier" when the discussion is concerned with this item.

Scope of the book

A tape recorder consists of two basic parts—mechanical (the transport mechanism) and electronic. This book is concerned with the latter, the term being used here in a broad sense to include everything other than transport. The subject of transports is sufficiently important and complex that another volume would be required to do justice to it. Therefore, only a cursory review of the functions and elements of a transport mechanism will be attempted. To the extent that the transport creates problems of an electronic nature—for example, noise on the tape—due attention shall be paid to it.

It is difficult to draw a clear physical line between the electronics and the transport. Certain electronic elements are often mounted on the transport so that electronic and mechanical functions may be controlled simultaneously, or for other reasons. And, of course, the heads are mounted on the transport mechanism. It should be explicit from the viewpoint of this book that the electronics includes not only the amplifier but also the heads and the tape.

The various chapters are concerned with the electronic functions of the tape recorder, why these functions are called for and the means of performing them. To provide perspective, the recorder is first pictured in context, that is, as part of a complete audio system. Behavior of the heads and the tape is examined. The fundamental problems of frequency response, distortion and

² Since the preamplifier is an integral part of the amplifier, it will not be considered as a separate unit. The term amplifier will be understood to include preamplifier.

noise are dealt with in terms of design and of extracting optimum performance from a given recorder. Requirements for high-quality performance are given. Basic circuitry is described and evaluated.

There are many special types of tape recorders, such as those used for industrial testing, electronic computing, scientific measurement, video recording, motion-picture recording, etc. No attempt is made here to cover these, which merit extensive but separate discussion. The fundamental concern of this volume is with tape recorders, either of the professional or moderate-price variety, commonly employed for audio recording and reproduction, especially in home music systems. All tape recorders share certain common principles so that the present discussion is of value to the reader interested in tape recorders used outside the field of audio.

In dealing with a subject such as the tape recorder, it is possible to expand in many directions. Thus, one could write on the nature of sound, on music, on the manifold uses for audio tape recorders, on the art of tape editing, on microphone techniques. These topics are not treated here. Not that they lack importance, but it is the desire of the authors to concentrate on the purpose at hand, which is to explain the electronics of the tape recorder.

In this book the authors seek to explain how tape recorders work, how desired objectives are attained through appropriate design. They have been very conscious of the practical side of the matter and have focused more on recorders as they are than as they ought to be. As a result they have acquired a debt of gratitude to various manufacturers who have supplied schematics, photographs, charts, and other materials for this book. Among these are Ampex Audio, Inc., Audio Devices, Inc., Brush Electronics Company, Concertone [American Electronics, Inc.], Dynamu Magnetronics Corp., Magnecord, Inc. [Div. Midwest Instruments Co.], Minnesota Mining & Mfg. Co. [3-M Co.], Pentron Corp., Presto Recording Corp., Shure Brothers, Inc., Viking of Minneapolis and Wilcox-Gay Corp.

Although the entire text of this book is new, the authors have depended in several sections upon materials appearing in magazine articles previously written by them. Accordingly they wish to thank *Audio* and *Radio & TV News* for permission to use charts, tables, and other data which appeared in these articles.

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HENRY C. POLLAK

elements of a tape recorder

TO understand the tape recorder it is helpful to examine not only its components but also the audio system of which it is part. The elements of a complete tape recording system are shown in Fig. 101.

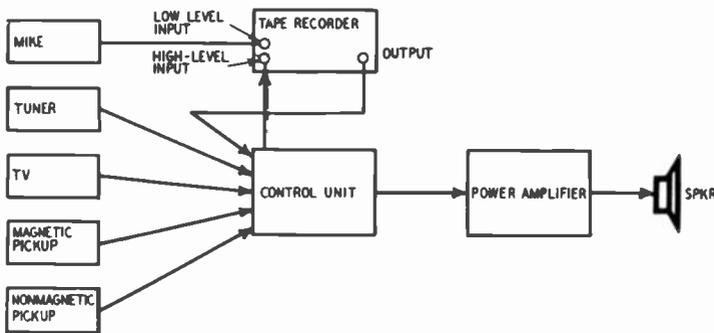


Fig. 101. Basic arrangement of a tape recording system.

Various audio sources are shown feeding into a control unit, a device which has a selector switch for choosing among the input sources, plus bass and treble controls, pre-emphasis and equalization for magnetic phono pickups, a gain control and sometimes a loudness control, high-cutoff filter, low-cutoff filter, etc. The audio signal goes from the control unit to a power amplifier and then to a speaker system. Almost all present-day control units also have an

output for simultaneously feeding the audio signal to a tape recorder. The power amplifier may consist of two units in either a stereo or a split-channel system where the highs go through one amplifier and the lows through another. Similarly, the speaker system may consist of one or several speakers fed through a cross-over network which apportions the frequency spectrum to the appropriate units. The complete system may use stereo speakers or several speakers spaced apart to obtain a distributed-source effect.

Tape recorders are almost always designed to record both from a low-level (a few millivolts of signal) and from a high-level source (about 0.1 to several volts of signal). In Fig. 101 high-level input sources are shown connected to the control unit. The tuner, TV and nonmagnetic phono could be fed directly into the recorder, but at the inconvenience of having to go through the process of changing connections when the source is changed, because tape recorders customarily do not have the ample selection facilities that control units do. As a rule, recorders do not provide the equalization required by magnetic phonograph cartridges to obtain flat frequency response and, therefore, they cannot satisfactorily accommodate the signal directly from a magnetic cartridge. However, one occasionally finds a recorder that is an exception to this rule.

In playback, the tape recorder feeds into the control unit just as do the other high-level audio sources. Or, if one chooses, the recorder output can go directly to an audio amplifier, but at the cost of having to make and unmake connections. (One can see that it is possible—sometimes, not always—for a feedback path to be set up, whereby the recorder output goes into the control unit, from there into the recorder input and again from the recorder output.)

Thus, the tape recorder plays a dual role in relation to the complete audio system. First, incoming signals are fed to it for recording purposes. Second, in playback it has the same role as other audio sources.

The term tape recorder tends to be somewhat obscure when it comes to defining what elements of a complete recording system it contains. Most moderate-price "home" recorders include several elements outside the block labeled "tape recorder." They generally include a power amplifier (infrequently meeting high-fidelity standards), an inexpensive speaker or speaker system and a medium-grade microphone. Some have a tone control, thereby

duplicating the function of a control unit, and in a few cases the unit has included an AM radio tuner. Thus one may well ask, Where does the tape recorder begin and end?

Fig. 102 shows what may reasonably be called the basic elements of a tape recorder. These may be sorted into transport and electronics, the latter consisting of the tape amplifier, the heads and the tape. This division is not a clean-cut one because the heads and tape are physically located on the transport. The amplifier consists of two basic elements—the record and playback sections. The latter does not necessarily include a power amplifier and speaker.

The path of the audio signal is fairly obvious. The incoming signals (high and low level) go into the record section (singly or together, depending upon the amplifier), then to the record

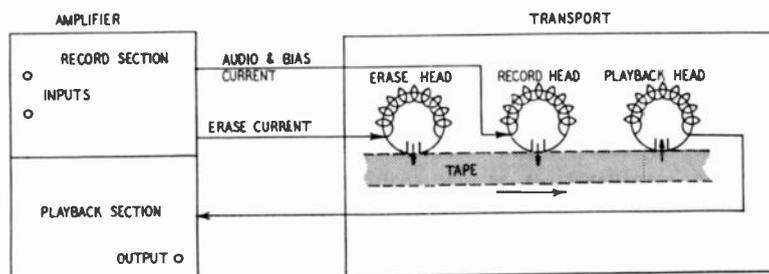


Fig. 102. Fundamental units of a tape recorder.

head and onto the tape. In playback, the signal from the tape enters the playback head, goes from there into the playback section and is finally delivered to the output.

Fig. 102 shows separate record and playback heads as well as separate record and playback sections. This is for diagrammatic convenience, although moderate-price home recorders (in the majority) use the same head for record and playback. They also employ essentially the same amplifier stages for both functions, the necessary changes being made through a switching system.

Variations in use of tape recorder elements

There are many variations of the basic arrangement of audio components for the purpose of recording and reproduction. One has already been mentioned—in some recorders the same head and same amplifier stages are used for both record and playback.

Playback only

Some tape machines are purely playback devices and may be

viewed in the same role as any other audio source. This is particularly true in the field of stereo, where the home user has little opportunity, equipment or know-how for making stereo recordings. There are similar machines for playing only conventional single-channel tape. In either case, the growing availability of pre-recorded tape, both single-channel and stereo, is increasing the demand for the so-called tape player, that is, the strictly playback machine which is comparable in its role to the disc phonograph.

Where it is desired only to play tapes and not record them, it is sometimes possible to dispense altogether with the tape amplifier. A few control units have a special input for accepting a signal directly from the playback head. The necessary equalization and amplification are provided by the control unit, much in the same manner as for a magnetic phono cartridge.

Mixing

A considerable number of variations are possible in the mixing of input sources. Thus one might employ a multiple-microphone setup, a combination of microphone and phonograph, a combination of microphone and electronic instrument, etc.

Sound-on-sound

“Sound-on-sound” recording where it is desired to record twice or more on a tape without erasing the previous recording, may

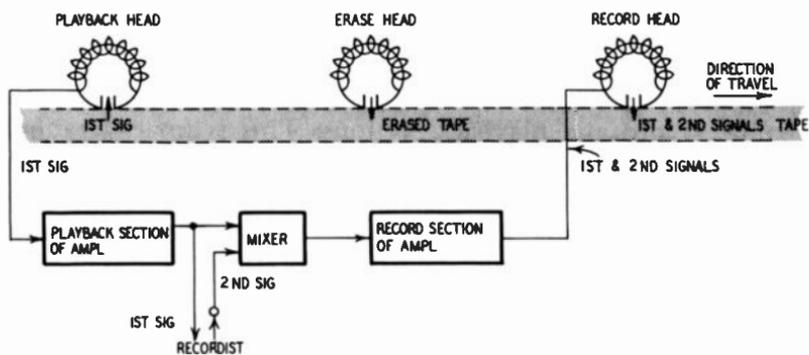


Fig. 103. Elements in sound-on-sound recording.

be likened to a double exposure in photography. A common illustration is a recording of the same individual playing two or more instruments at once. To do this it is necessary to locate the playback head so that it precedes the erase head, which is then followed by the record head in the normal manner; or else

an extra playback head (if the transport has room) is situated prior to the erase head. The sequence is shown in Fig. 103. After the first recording is made in the usual manner, the tape is re-wound. The first signal is then played by the extra or relocated playback head and fed into a mixer; the performer listens to the first signal through earphones and produces the accompanying second signal, which is also fed into the mixer. The two signals go into the record amplifier, then to the record head and onto the tape, which has been freshly erased by the erase head. The sound-on-sound process can be repeated to add a third signal, a fourth and so on.

Echo effect

Artificial reverberation or "echo effect" increases many listeners' pleasure by adding a feeling of spaciousness and warmth. Everyone who has ever sung in a bathroom is aware of the glamorizing effect of reverberation.

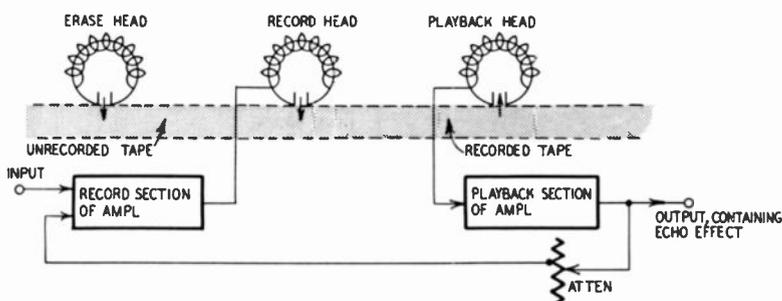


Fig. 104. Method for production of an echo effect.

Fig. 104 shows how an effect of this sort may be obtained with the aid of a tape recorder. After the signal is impressed on the tape by the record head, the playback head picks up this signal and adds some of it back to the record head, via the playback and record amplifiers. The amount of signal fed back is considerably attenuated, as in true reverberation. The degree of echo effect is partly determined by the distance between the record and playback heads; normal spacing, at 15 ips, causes the echo to appear about 1/10 second later. In specially designed tape machines, this time interval can be varied. Also, the quality of the echo effect can be improved in such machines inasmuch as they are equipped with several playback heads spaced along the tape, each of which

feeds the signals in successively attenuated form back to the record head.

Tape duplication

In the production of phonograph records a stamper impresses the entire arrangement of sound patterns all at once on the vinylite. In making tape duplicates, however, the master copy has to be played from beginning to end and one or more duplicates are made as the master is played, usually at a speed higher than normal to reduce the time. Fig. 105 shows the basic idea, of which

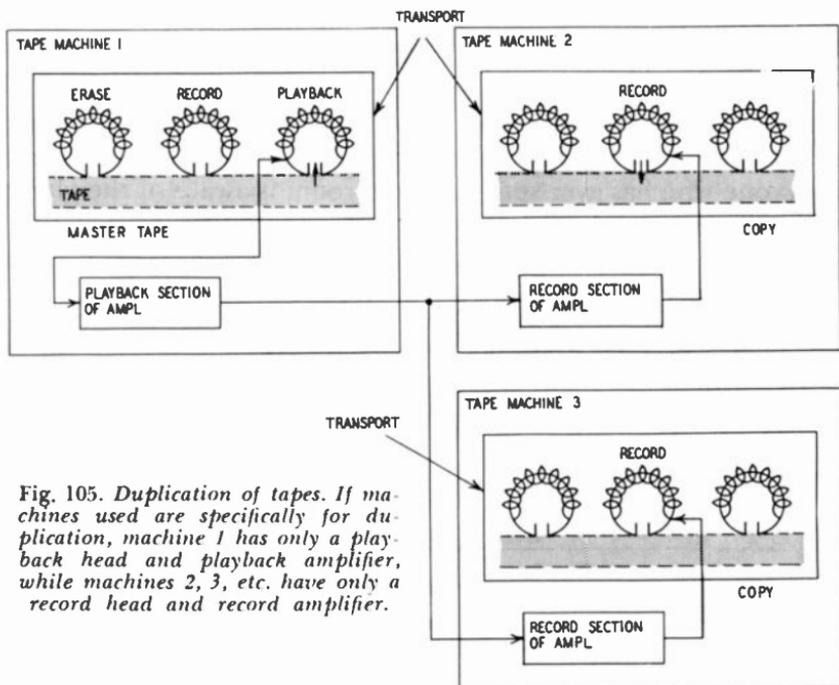


Fig. 105. Duplication of tapes. If machines used are specifically for duplication, machine 1 has only a playback head and playback amplifier, while machines 2, 3, etc. have only a record head and record amplifier.

there are some variations. The master tape is played on tape machine 1 and the signal, after leaving the playback section of the amplifier, goes to the record section of one or more tape machines. Where duplication on a mass basis is required, special machines are used, one being a master playback unit only (no record function) and the others designed for record only. In practice, up to about 10 or 12 record machines may be used with one master playback unit.

Amplifier elements

Fig. 106 shows the basic elements of an amplifier intended for

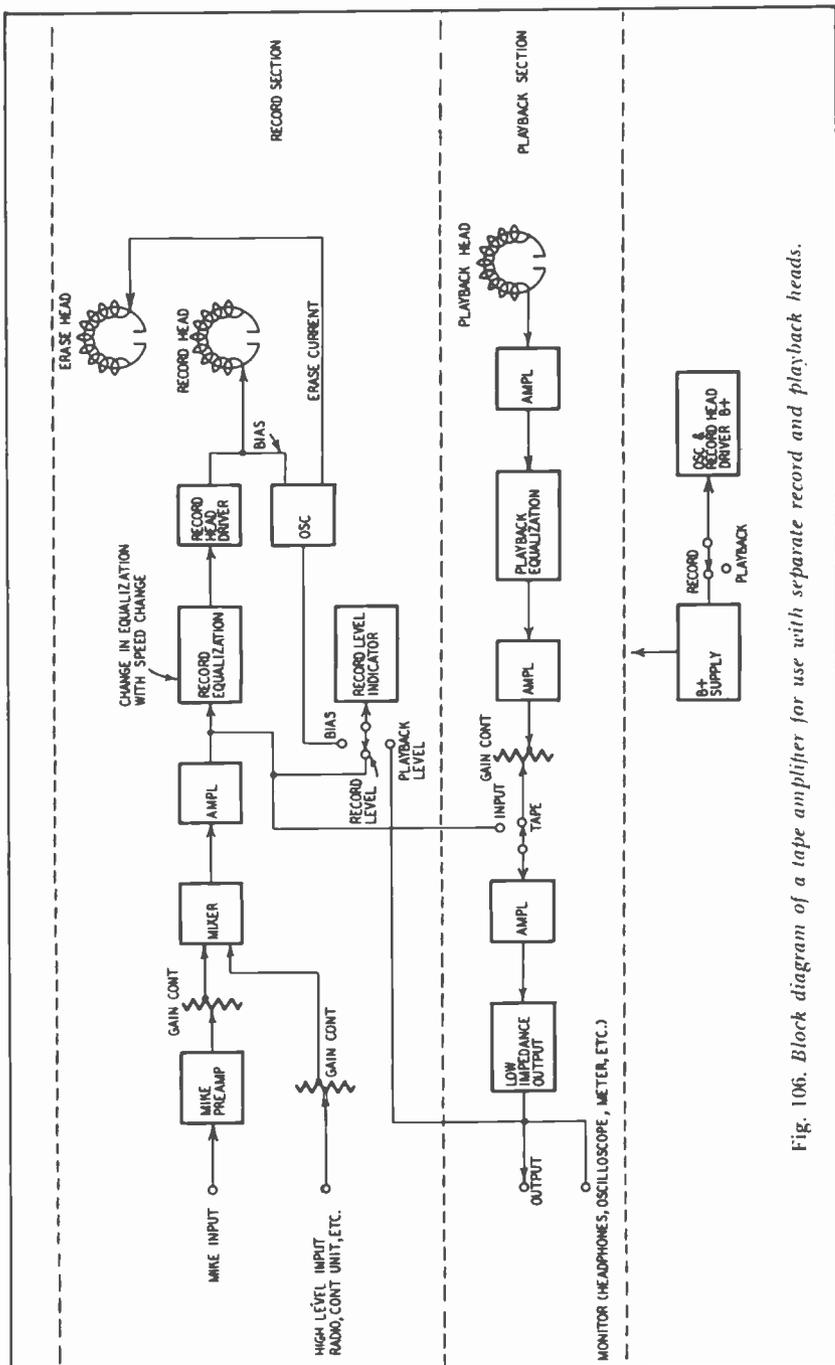


Fig. 106. Block diagram of a tape amplifier for use with separate record and playback heads.

use in a tape recorder having separate record and playback heads as well as an erase unit. This diagram represents a high-quality amplifier containing the functions generally considered desirable. The exact sequence of functions is not the same in all amplifiers of comparable quality but the dissimilarities among them are generally minor.

Because the signal from a microphone is only in the order of millivolts, an extra amplifier stage is required when recording from this source. Some machines contain facilities for mixing low- and high-level inputs. Others require an external mixer. The relative levels of the low- and high-level incoming audio signals are adjusted by the respective gain controls for each source before they are combined in the mixer. In most home recording, either the microphone input or the high-level input is used alone so that the gain control of the one not in use is turned all the way down. Following the mixer comes further amplification and then equalization to provide the recorded frequency characteristic. This, in conjunction with the playback frequency characteristic, will result in a more or less flat response over the audio range in playback. Especially in higher-price machines, the recorded frequency characteristic conforms to the NARTB (National Association of Radio & Television Broadcasters) standard.

The equalization used in recording depends upon the tape speed. If the recorder operates at two (or more) speeds, provision is usually made for modifying the equalization when the speed is changed.

After equalization and before the signal goes to the record head, a third stage of amplification is required. This may be termed the record-head driver. Along with the audio signal, there is also delivered to the head a high-frequency current called bias, ordinarily ranging between 30,000 and 100,000 cps. The bias current reduces distortion to an acceptable level and increases the amount of signal recorded on the tape. Bias may be likened to a catalytic agent in a chemical reaction, promoting the desired process.

The oscillator shown in Fig. 106 has a dual function. In addition to providing bias for the record head, it provides a fairly substantial amount of current to enable the erase head to perform its function efficiently. Although a few recorders in the past have used separate bias and erase oscillators, it is now almost standard recorder practice to employ a common oscillator for both of these functions.

In playback, the signal from the head is of very low level and goes through a stage of amplification before being equalized to

produce the desired flat frequency response over all or most of the audio range. Next comes a second stage of amplification, followed by a gain control, further amplification and a low-impedance output stage. The latter permits a substantial run of cable between the tape recorder and the next audio component (usually the control unit) without undue loss of high-frequency response due to the capacitance of the cable. Moderate-price recorders, however, generally have a high-impedance output so that only a few feet of cable can be used safely.

The principal purpose of the record-level indicator is to show the user whether he is recording at a satisfactory level. Too high a level produces tape distortion. At a very low level the noise present in all audio systems will be unduly large compared to the desired signal. The record-level indicator in a high-quality amplifier is customarily employed for two additional functions. One is to measure the bias current supplied to the record head. Insufficient bias increases tape distortion although it may improve high-frequency response. Too much bias attenuates treble response and possibly also increases distortion. The other function is to measure the signal level on a tape that is being played back. It may be desirable to compare levels on various recorded tapes or to set correctly the level of a signal being fed to a following audio component.

Fig. 106 shows that the last two stages in the playback section can be switched to either the earlier playback stages or the record stage. Thus, when a recording is being made, the user can switch between the incoming and the recorded signals to determine whether the recorded audio signal is an adequate facsimile of the incoming one.

Finally, Fig. 106 shows that the record and playback sections are fed by a common power supply. To use the tape recorder for playback, B plus to the oscillator and to the record-head driver is removed. This prevents accidental erasure and possible recording of noise.

Amplifier for a two-head machine

Professional and semiprofessional tape recorders are customarily three-head machines. That is, they employ separate record and playback heads (plus an erase head) which permit simultaneous recording and playback. This enables the user to determine whether a recording is proceeding satisfactorily and facilitates adjustment and alignment of the machine. However, the majority

of home units, for reasons of economy, have only two heads, one of which serves for both record and playback. The other, of course, is the erase head. Thus the cost of a head and of several amplifier stages is saved, with a certain amount of relatively inexpensive switching substituted to permit most of the amplifier to serve in a dual capacity for record and playback.

Fig. 107 shows the basic elements of the tape amplifier in a typical moderate-price recorder with a single record-playback head. Although most such recorders also include a power amplifier and a speaker system, these are not considered part of the amplifier proper and are therefore omitted from the diagram and discussion.

Moderate-price recorders seldom provide mixing facilities with separate gain controls for the low- and high-level inputs. Instead, there is usually a common gain control. However, inasmuch as many audio sources, such as tuners, TV sets, etc. have their own gain controls, adjustment of the low- and high-level sources to the desired relative levels (when both are used at once) can often be accomplished by means external to the tape amplifier. Although in some home recorders it is possible to mix both sources more often this cannot be done because inserting the high-level cable into the preamplifier opens the low-level connection to the gain control (thereby eliminating hum and noise from the extra amplification stage for low-level sources). Mixing must then be accomplished by external means. A few audio control units afford mixing facilities; the majority do not. However, separate mixers can be purchased.

Following the gain control comes an amplification stage, record equalization and the record-head driver. In some amplifiers different equalization is used in record than in playback. On the other hand, a very substantial number (perhaps the majority) of home recorders employ the same equalization in record and playback, as shown by the dash-line connections.

Without any equalization whatever, the frequency response of a tape recorder exhibits a substantial drop at both the bass and high ends. Therefore, both bass and treble boost are required. For best results, treble boost should take place essentially in recording and bass boost mostly in playback. However, partly as an economy measure and partly to overcome hum problems, many home recorders accomplish half the treble and bass boost in recording and the other half in playback, thus permitting use of the same equalization in both modes of operation.

Fig. 107 shows that, as in Fig. 106, the oscillator feeds the erase

head and supplies bias to the record head in the record mode. In playback, B plus is removed from the oscillator to prevent erasing the tape. Also, the record-level indicator functions only in the record mode.

The simultaneous switching functions in an amplifier designed for a two-head recorder can be fairly extensive and are at least three in number: (1) supplying the first amplifier stage with either the microphone signal or with the signal from the head; (2) feeding the signal from the last amplifier stage (labeled record-head driver) either to the head or to the output; (3) shutting off oscillator B plus in the playback mode. In addition, the record-level indicator is often disconnected in the playback mode, and different equalization may be introduced when changing from record to playback. Also, though not shown in Fig. 107, different

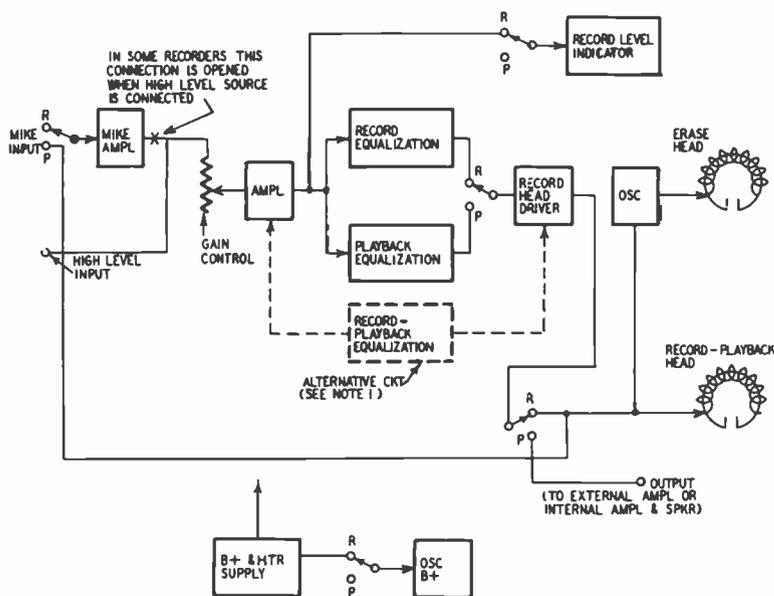


Fig. 107. Basic elements of a tape amplifier for use with a record-playback head. Many two-head recorders use the same equalization in record and playback. In the diagram shown above, all switches operate simultaneously. (R means record, P is playback.)

equalization may be provided for operating at different tape speeds. Thus there may be as many as six simultaneous switching functions in all.

Other tape recorder elements

Let us take a brief look at the other basic elements of a tape re-

order in terms of the functions they serve: the transport, the heads and the tape. Inasmuch as this book is essentially concerned with the electronics of a tape recorder, relatively little will be said about the transport. However, greater attention is given to the tape and to the heads in view of the important bearing they have upon design and operation.

Heads

The tape recorder employs three types of heads: erase, record and playback. In most home recorders the record and the playback functions are served by the same head which is switched from one function to the other as required. Some recorders employ heads that also incorporate the erase function. However, these actually consist of two electrically separate heads contained in the same housing. A typical record-playback-erase head is shown in Fig. 108.

A head that has quite recently become of importance is the "in-line" unit used for recording and playback of stereophonic

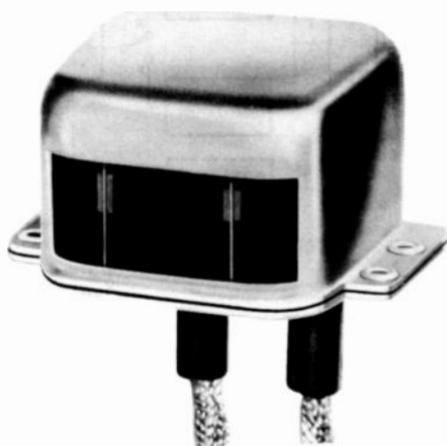


Fig. 108. Combination record-playback and erase head (half track.) Courtesy, Shure Brothers, Inc.

sound. This consists of two sections, each equivalent to a separate head, mounted directly above one another so that their gaps are in a vertical line (Fig. 109). One section records or plays the upper part (track) of the tape while the other simultaneously operates on the lower part. Each section must be small enough so that the two together occupy about the same space as a con-

ventional head. For stereo purposes, two conventional heads can also be used as shown in Fig. 109. These heads are spaced 1.25 inches apart, one operating on the lower half of the tape and the other operating on its upper half. The conventional arrangement is that for a tape viewed from the backing (coating toward the heads) and traveling from right to left, the lower portion bears track 1, for the left speaker, while the upper portion bears track 2, for the right speaker. For single-channel material, the heads are situated opposite track 1.

Single-channel recording may be either full-track or half-track, that is, the head may be designed so that its active portion (the gap) spans either the full width of the tape or about half. For professional purposes, full-track recording is customarily employed because of greater signal output and because editing of the tape is practicable only when one track is recorded. Most home recorders, however, employ half-track heads. Assuming that the tape moves from right to left, the lower half of the tape is recorded. The reels may then be reversed and the other half of the tape recorded, thus doubling the amount of playing time obtained from a reel of tape.

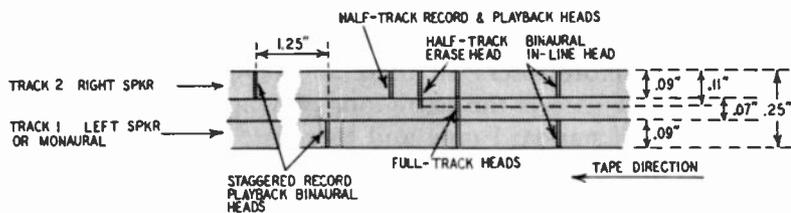


Fig. 109. Tape tracks, dimensions and head (gap) locations, viewed with the tape backing toward the reader and the coating toward the heads.

A full-track head is exactly that, its gap covering the entire width of the tape. The gap of a half-track head, however, usually covers about 0.09 inch. Two tracks add to about 0.18 inch, leaving 0.07 inch in the middle of the tape as a safety island to prevent the overlapping of tracks and consequent cross-talk between the recordings on the upper and lower tracks. The erase-head gap spans about 0.11 inch to insure full coverage of the recorded track, with something to spare. These various dimensions are shown in Fig. 109.

Assuming the tape travels from right to left, in practice the lower edge of a half-track head is usually not exactly flush with the bottom of the tape. Instead, it is located 10 or 20 mils (thou-

sandths of an inch) above the bottom, thus consuming some of the safety margin of 70 mils. If 15 mils, for example, are thus used for each track, the safety island is reduced to 40 mils.

The full-track record and playback heads, because of the greater tape width they cover, result in an 8- or 9-db-higher signal output, everything else being equal. As a result, a higher signal-to-noise ratio may be obtained with full-track heads although, due to the fact that they also pick up more hum and tape hiss, the difference is often only 3 db or so.

The tape

Virtually all tape made today for audio recording purposes utilizes a plastic base coated with a magnetic substance. The coating is a mixture of ferrous oxide and synthetic resins which enable the oxide to adhere firmly to the base.

The magnetic tape ordinarily used is about 0.25 inch wide and available in three thicknesses. The thinner tapes permit increased playing time for a given reel size because greater lengths can be wound on the reel. Standard tape is about 0.0021 inch thick, the coating being about 0.0006 and the base 0.0015 inch. Long-playing tape, introduced a few years ago, is two-thirds as thick and therefore offers an increase of 50% of playing time. Of more recent date is the extra-long-playing tape, which is half the thickness of standard tape and therefore doubles the playing time of a reel. Unfortunately, it is too fragile for general home use.

The reel size most common in home use has a diameter of 7 inches. It accommodates 1,200 feet of standard tape, 1,800 feet of long-playing tape or 2,400 feet of extra-long-playing tape. At 7.5 ips (inches per second), the speed most commonly employed by home recorders for high fidelity, 1,200 feet translates into 32 minutes of playing time. The thinner tapes offer 48 or 64 minutes per track on a 7-inch reel. If the tape is recorded half-track, as is usual, a two-track recording can last 64, 96 or 128 minutes; that is, from about one to two hours.

Most professional machines can take a reel up to 10.5 inches in diameter, which holds twice as much tape as a 7-inch reel. This doubles the playing time, resulting in a maximum of about $4\frac{1}{4}$ hours. However, professional machines usually operate at 7.5 and 15 ips, so that with a 10.5-inch reel they can provide the same playing time as a machine accommodating only 7-inch reels and operating at 3.75 and 7.5 ips. Reels greater than 10.5 inches

can be accommodated by a few professional machines while reels smaller than 7 inches can be played by virtually any unit.

Another distinction that can be made is that between regular and high-output tape. Output refers to the amount of signal obtained from the tape playback at a given level of distortion. Part of the increase in high-output tape usually results from the ability of the tape to accept a stronger magnetic field in recording without an increase in distortion. And part results from the greater sensitivity of the tape, that is, a greater recorded flux for a given magnetic field generated by the record head. There are also variations in output between brands and between batches within the same brand. These variations, however, are usually minor compared with the difference between regular and high-output tape, which is 8 db or more.

Tape must meet several mechanical requirements—strength, smoothness and limpness. Not only is the tape subject to considerable tension because the supply and takeup reels tend to rotate in opposite directions, but sudden starts and stops and rapid wind and rewind subject the tape to additional stress. A breaking strength of several pounds is therefore required. Also, the tape must be able to withstand considerable strain before becoming permanently stretched.

Tape must maintain very close contact with the heads for good results; therefore, smoothness of the coating is vital. Not only does a rough coating prevent continuous close contact, but it also causes undue head wear and noise due to vibration against the heads. Inasmuch as many recorders use pressure pads to hold the tape firmly against the heads, it is also important that the back of the tape (the base) be smooth. Tapes contain small amounts of various lubricants to promote smooth operation.

To enable it to hug the heads closely, the tape must be limp. This quality further permits the tape to make sharp turns around guides and tension devices with ease.

The transport

The fundamental purpose of the transport mechanism is to move the tape past the heads at a rate which is both uniform and accurate. Erratic motion manifests itself in wow, flutter and noise, which are deviations in the frequency of a tone. A transport of professional quality keeps the average value of these deviations below 0.2% of a test frequency (usually 3,000 cps) recorded on

the tape. (See Fig. 110 for photos of tape transport mechanisms.)

Wow is evident as slow variations in pitch (a few times a second) which cause prolonged notes, such as those of a piano, to go painfully sour. Flutter refers to pitch variations substantially higher in frequency that produce a warbling effect. Extremely rapid



Fig. 110. *Tape transport mechanisms (tape decks)*. Upper: photo courtesy Pentron Corp. Lower photo courtesy Viking of Minneapolis.

speed variations result in noise. The last phenomenon may not be due to the transport but to tape that is not smooth or to improperly adjusted pressure pads. This causes high frequencies to have a coarse, grainy quality and is sometimes referred to as frequency-modulation noise. The principal sources of frequency-

modulation noise are the varying frictional forces acting upon the tape as it passes over the recording heads and guides. This action is similar to that of drawing a bow across a violin string.¹

Inaccurate motion manifests itself as a steady deviation from correct pitch, which may or may not be bothersome, depending upon the musical training of the listener's ear. High-quality transports maintain an accuracy of speed better than 0.2%, which means that a recording supposed to last exactly 32 minutes will deviate no more than 3.8 seconds in either direction.

Fig. 111 shows the basic elements of a transport mechanism. The reel of tape to be recorded or played is mounted on the left

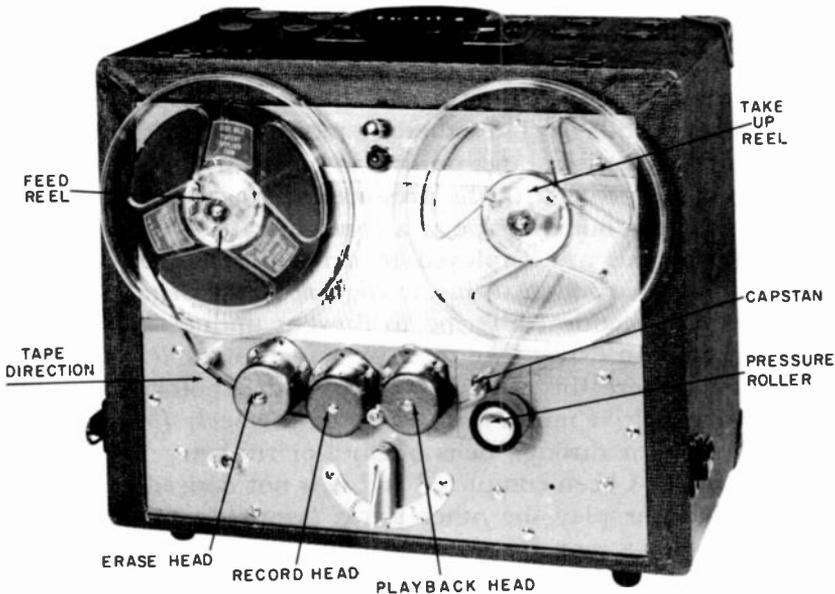


Fig. 111. *Tape recorder showing the principal exterior components of the transport mechanism.* Courtesy, Presto Recording Corp.

hand spindle while a takeup reel is mounted on the right one, although in many recorders the opposite arrangement is used. In sequence, the tape moves past the erase, record and playback heads. If the machine is being used for playback, the erase and record heads are inactivated. In the majority of home recorders, the record and playback functions are performed by the same head which is switched from one function to the other.

The tape is moved at the required speed as the result of being

¹ 3M Co., *Sound Talk*, Bulletin No. 18.

pinched between a motor-driven capstan and a spring-actuated rubber roller, called the pressure roller. When it is desired to play or record, a lever causes the pressure roller to spring against the capstan, and the roller together with the capstan drives the tape. Guides keep the tape in line with the heads and prevent its weaving up and down. The means for keeping the tape in firm contact with the heads is not shown.

The feed and takeup reels tend to rotate in opposite directions, though not with such force as to rupture or stretch the tape. In motion, the tape moves not only against the torque of the supply reel but also with the torque of the takeup reel which tends to rotate at a speed considerably greater than that required to wind the tape. Obviously, the tape would break were it not for a device that permits the reels to slip in one fashion or another. Slippage is provided by using clutches or belts or, where the reels are directly motor-driven, by operating these motors substantially below their rated voltage. Thus there is more or less a balance of forces at each end of the tape, pulling in opposite directions. The capstan in conjunction with the pressure roller acts as a metering device which pays out the tape at a constant rate.

Various methods are employed to drive the capstan, seeking sufficiently positive action to insure high accuracy of motion, yet with enough mechanical filtering to prevent undue wow, flutter and noise. Capstan drives take three principal forms: (1) a direct-motor drive, where the capstan is part of the motor shaft; (2) a linkage to the drive motor through an idler wheel; (3) a linkage to the drive motor through belts of cloth or rubber.

After a reel has been completed and it is not desired to reverse reels to record or play the other track (assuming half-track recording), the tape may be rewound. The pressure roller is disengaged from the capstan and, through mechanical or electrical means, greater driving torque is applied to the feed reel than the takeup reel. On the other hand, to wind in the opposite direction, greater torque would be applied to the takeup reel.

Although very good results have been obtained by using one motor to perform the three functions of driving the capstan, feed reel and takeup reel, top-quality transports employ three motors, one for each of these functions. The highest-price machines employ a hysteresis-synchronous motor to drive the capstan. This permits the greatest timing accuracy since the speed is exactly determined by the frequency of the ac power line, customarily 60 cycles.

Not shown in Fig. 112 is the means employed to maintain firm

contact between the tape and the heads. Such contact is vital to maintain high signal output, particularly at high frequencies. Two methods are in use. Virtually all moderate-price recorders employ a pressure pad, that is, a piece of felt mounted on a metal arm, which is held by spring pressure against the back of the tape as it moves past the heads. The other method, commonly used on professional-grade recorders, is to employ guides and rollers so located as to cause the tape to follow a course assuring firm contact with the heads.

The subject of transports merits voluminous discussion, and all that can be done here is merely to list various other elements of transports, some of which are found only in the better mechanisms: brakes for bringing the reels to a rapid halt; means for changing the speed at which the tape is driven; a mechanical interlock which prevents rapidly rewinding or winding the tape when

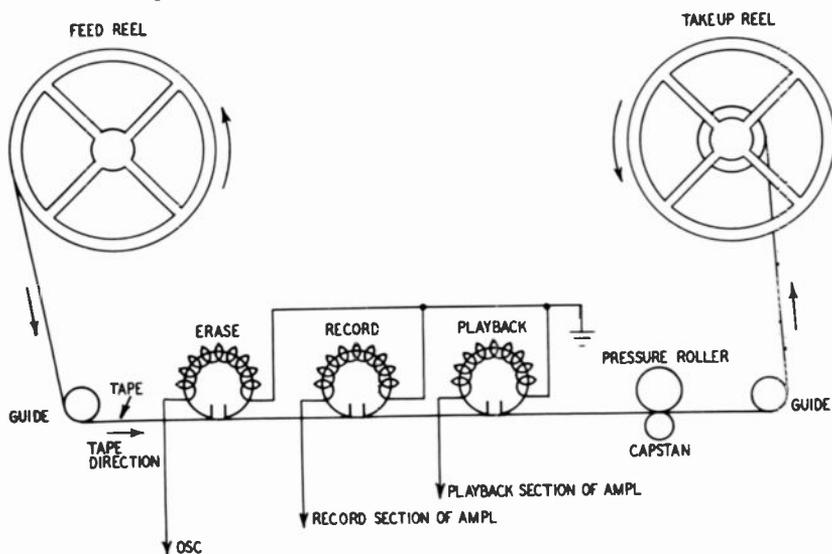


Fig. 112. Drawing of the principal parts of the transport mechanism.

the mechanism is set for record or play; a tape lift which spaces the tape slightly away from the heads during rewind or forward wind to reduce head wear caused by the abrasive action of the tape; a mechanical arrangement which permits ready access to the portion of the tape opposite the record and play heads to facilitate marking the tape for editing purposes; automatic shutoff of the transport if the tape breaks or runs out; space for mounting additional heads to permit special uses such as sound-on-sound and

echo-effect recording; automatic withdrawal of the idler wheel (if this method of capstan drive is employed) from the motor shaft and capstan when the transport is shut off, to prevent the idler from developing flats; a tape position indicator so that the user can readily locate any portion of a tape recording; Mu-metal covers for the heads to shield them from hum pickup, particularly by the playback head.

characteristics of a high-quality tape amplifier

At different prices one expects to find variations in terms of design, construction and performance in amplifiers. Also, there may be differences attributable to the purposes which the tape recorder is intended to serve; not every tape recorder is meant for high-fidelity service. Since it is not feasible in these pages to examine all types of amplifiers, the most informative approach appears to be to deal with the kind of amplifier capable of yielding top performance in audio work.

Electrical performance

In terms of electrical performance, a tape amplifier should meet high-fidelity standards with respect to frequency response, distortion, signal-to-noise ratio and equalization. Moreover, it should have sufficient gain to accommodate various input signals as well as to drive following audio components in playback.

Frequency response

In terms of electrical performance—prior to the speaker—a high-fidelity system should span the range of at least 20–20,000 cycles with a tolerance of about ± 1 db. However, this frequency requirement must be modified in the case of a tape recorder, the extent of modification depending upon tape speed. The lower the speed, the less can reasonably be expected in the way of high-frequency response. Low-end response, however, varies relatively little with tape speed.

The present state of the art of tape recording, which takes into account the characteristics of the tapes and heads now available, permits fairly smooth response to be obtained out to 15,000 cycles at speeds of 7.5 ips and higher. Such extended response at 7.5 ips, however, involves sacrifices in terms of distortion and/or signal-to-noise ratio. In the case of amplifiers that incorporate substantially all available means of reducing noise and distortion, the amount of such sacrifice still permits high-fidelity performance while maintaining substantial response to 15,000 cycles. In amplifiers of lesser grade, maintaining response to 15,000 cycles can entail a serious degradation with respect to distortion and signal-to-noise ratio.

In the experience of many listeners there is virtually no difference to the ear between a response nearly flat (no more than 2 db down) to 12,000 cycles and response virtually flat to 15,000 cycles. Moreover, above 10,000 cycles, audio sources such as phonograph discs, tuners, recorded tape, etc. often contain noise and distortion components equal to or exceeding the desired audio information. At 7.5 ips, the speed predominant in home use, lowering the requirements to 12,000 instead of 15,000 cycles often permits a significant improvement in signal-to-noise ratio and/or distortion. Thus, a tape amplifier to be used in conjunction with top-flight heads at the 7.5-ips speed should provide response virtually flat to 12,000 and possibly to 15,000 cycles.

The 3.75-ips speed is also very common in home use. Attainable high-frequency response varies directly with tape speed so that at 3.75 ips the tape amplifier in conjunction with the heads should be able to provide response to 6,000 cycles and perhaps to 7,500.

At 15 ips, used by professionals and home recordists who seek the utmost in quality, response should extend to at least 15,000 cycles. Higher response has relatively little value and it is generally advisable to sacrifice response above 15,000 cycles, to improve the signal-to-noise ratio and reduce distortion.

At the bass end, taking into account head and tape characteristics, the amplifier should provide equalization which assures response no more than 3 db down at 50 or possibly 30 cycles. It may well be asked why it would not be better to require *flat* response down to 20 or 30 cycles, especially since speaker systems reproducing satisfactorily down to 20 or 30 cycles are becoming more common. The answer lies mainly in the large amount of low-frequency equalization which would be required in playback.

accentuating low-frequency noise (and hum frequencies) and thereby deteriorating the signal-to-noise ratio. Thus, the present NARTB standard of tape-recorder frequency response applicable to 15-ips recording covers the range from 50 to 15,000 cycles and permits response 4 db down at 50 cycles. If a tape recorder is 3 db down at 30 or 50 cycles, this does not necessarily mean a sharp cutoff below this point; there can still be usable output, perhaps 6 to 8 db down, at 20 cycles.

Uniform frequency response over the feasible range is important. Audible peaks should not be present. On the other hand, in view of the complexities of equalization, a standard of ± 1 db permissible deviation from flat response within a prescribed range, while desirable, is somewhat rigorous, especially since equalization requirements tend to vary somewhat from one tape to another even within the same brand. Quite acceptable reproduction of the original sound can be had if the tolerance is ± 3 db. Response flat within ± 2 db is barely distinguishable from the original to the human ear and may be considered a suitable standard, although a few of the professional recorders when carefully adjusted manage to stay within ± 1 db. If a listener moves to another seat or turns his head slightly, the resulting change in relative frequency response over the audio spectrum is much greater than the ± 2 -db deviation due to the tape recorder.

Many tape recorders are designed to operate at two speeds, usually 7.5 and 3.75 ips for home use and 15 and 7.5 ips for professional use. To the extent that economy is an important factor, it is difficult for an amplifier to serve both speeds with equal faithfulness. If a sacrifice is required at one speed or the other with respect to frequency response, it is logically consistent that performance at the higher speed should be given preference for it is the higher speed that also provides superior results in terms of signal-to-noise ratio and distortion.

Distortion

In recording, the determining factor with respect to distortion should be the tape, although a poorly designed record head can overload before the tape does, particularly at low frequencies. In any case, the record amplifier should produce no appreciable distortion.

Maximum permissible record level is customarily the 400-cycle signal level which produces a given amount of harmonic distortion, sometimes given as 1%, sometimes as 2% or as 3%. The

quently, the record amplifier should have hum and noise characteristics as good as those of the playback section.

All in all, in a well-designed and well-constructed tape recorder, the dominant cause of noise should not be the amplifier or the heads (which would be adequately shielded against hum) but the tape itself, which has inherent noise that cannot be eliminated.

A signal-to-noise ratio of 55 db may appear low as a measure of high-quality performance in a tape recorder, particularly when compared with ratios of 70, 80 or 90 db claimed for other audio components, particularly power amplifiers. On the other hand, it is not particularly low when compared with ratios for other audio sources in light of the problems in tape recording.

The magnetic phono channel of most control units provides a signal-to-noise ratio in the range of 50 to 60 db, which is comparable to the 55 db of a first-rate tape recorder. Yet the phono channel of the control unit has an easier task than the playback section of the tape amplifier. *Peak* output from magnetic cartridges usually ranges from about 30 mv (millivolts) to as high as 100. Compared with the 10 mv or so peak output from a playback head, this is a difference of at least 10 db. Moreover, a tape amplifier that conforms to NARTB equalization must produce a relatively enormous amount of bass boost. Equalization for disc recordings generally requires bass boost starting at 500 cycles, but in the tape playback amplifier bass boost starts at 3,180 cycles (NARTB equalization). The tape playback amplifier has a total boost of 36 db when NARTB equalization is used whereas the phono channel incorporates but 20 db of boost when compensating the RIAA recording characteristic now almost always employed for discs.

Turning to the FM tuner, a transmitting station is considered excellent when its transmitted signal has a signal-to-noise ratio of 55 db. The best FM receivers have a ratio of 55 to 60 db.

In discussing the tape recorder's signal-to-noise ratio, it was presumed that the playback head is of the full-track variety commonly, though not always, used for professional quality. However, if a half-track playback head is used, as in most home recorders, the tape recorder may have a somewhat lower signal-to-noise ratio inasmuch as a full-track head (assuming full-track recording) has about 8- or 9-db higher output. However, the difference between half- and full-track heads with respect to signal-to-noise ratio is likely to be closer to 3 or 4 db since the full-track head picks up more tape hiss and more hum as well as more audio signal. Thus, a tape recorder using half-track heads may be con-

sidered as having a good signal-to-noise ratio if this exceeds 50 db.

Equalization

Without question, a top-quality tape amplifier intended for high-fidelity service should incorporate equalization that conforms to present accepted standards, whether or not these standards are official. Thus the tape recorder can produce tapes that sound right on other machines and, conversely, it can sound right when playing tapes made on other machines. The latter requirement is the more important one because a tape recorder may be used to reproduce some of the excellent prerecorded tapes reaching the market in increasing numbers.

How accurate should equalization be? The answer is essentially the same as with respect to uniformity of frequency response. Thus a deviation of ± 2 db over the range of 50 to 15,000 cycles at 15 ips, 50 to 12,000 cycles at 7.5 ips and 50 to 6,000 cycles at 3.75 ips can be considered good.

A substantial number of machines, particularly the moderate-price ones, shy away from maintaining response so that it is no more than 3 db down at 50 cycles. By allowing the response to drop substantially at the low end, problems of hum and noise are significantly reduced. Similarly, many recorders do not attempt to extend the high end because this requires improvements with respect to distortion and noise that the price of the machine does not permit.

Most tape recorders operate at two speeds, a few at three. Each speed requires substantially different equalization in the record section of the amplifier while there may or may not be a substantial difference required in the playback amplifier, depending on the speed involved. The 7.5- and 15-ips speeds often employ substantially the same playback equalization, while 3.75 ips requires considerably different equalization.

A high-quality tape amplifier permits changing equalization according to speed. Too often, however, amplifiers do not contain such switching facilities. Therefore, response may be perfectly satisfactory at one speed but not at the other or, inasmuch as some machines use a compromise equalization, response at neither speed may be as good as possible.

Extended treble response at the lower speeds, 3.75 and 7.5 ips, is feasible, at least to an extent, through very substantial amounts of treble boost in the record amplifier. However, this entails the risk of increased distortion because of the extent to which the

high frequencies are boosted. Therefore a high-quality amplifier will follow a course of moderation, avoiding treble boost which attains a slight improvement in treble response at the cost of a large increase in distortion.

Gain

The tape amplifier should have sufficient gain to accommodate various audio sources when recording and to furnish the required driving signal to either a control unit or a power amplifier in playback.

Virtually all high-level signal sources—control units, radio tuners, TV sets, and ceramic and crystal phonograph cartridges—have peak outputs of at least 0.5 volt. Thus a tape amplifier which can be driven to full record level by an 0.5-volt input might be sufficient. However, there should be a margin to allow for the occasional so-called high-level source which does not produce 0.5 volt on peaks. Also the reserve should allow for the fact that tapes of the near future, for the same amount of distortion, may be able to accept more signal from the record head with correspondingly greater tape output. Allowing about 10 db of reserve, this means that the input sensitivity of the amplifier should be on the order of 0.1 to 0.2 volt.

For low-level sources, a sensitivity of at least 1 to 3 mv is required. A typical dynamic microphone at a distance of 2 feet produces about 2-mv output when driven by a human voice at average level. Peaks and loud tones produce considerably greater output. Thus a sensitivity of 1 to 2 mv appears adequate.

Most control units can be driven to their rated output by input signals below 0.5 volt, often by as little as 0.1 volt. Power amplifiers generally can be driven to their rated output by signals varying from 0.5 to 2 volts. However, seldom is a tape recorder fed directly into a power amplifier. Accordingly, a tape recorder with a peak output of 1 to 2 volts should meet virtually all practical requirements so far as high-fidelity and other audio systems are concerned.

If the tape amplifier has much greater input sensitivity or higher output level than is required, this is not necessarily a virtue. Excessive gain may mean excessive noise from stages following the volume control, either in record or playback. Excessive gain may involve problems of stray feedback and consequent oscillation. Excessive tape-recorder output may overload the following control unit, particularly if the control unit does not have a "level-

set" potentiometer which permits cutting the input signal to a level that will avoid significant distortion.

Mechanical features

The mechanical features of a tape amplifier are related in part to its electrical performance, convenience of operation, durability of the amplifier and minimization of servicing requirements.

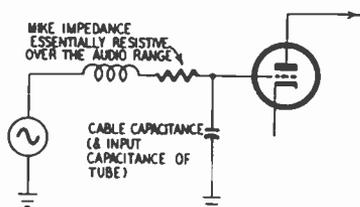
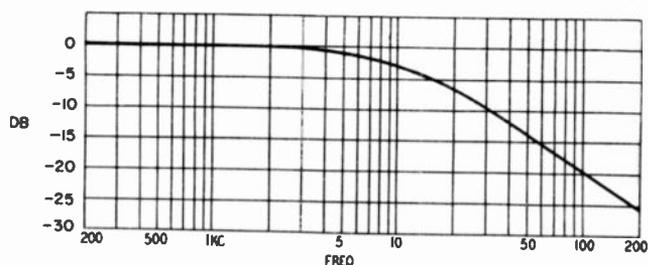


Fig. 201. Typical high-frequency droop due to cable capacitance when using a high-impedance microphone.

While electrical performance is first in importance, it is no small thing to the recordist to have those features which provide ease of recording, editing, etc., reduce the chance of the recording going awry and which insure long and reliable service.

Inputs

Virtually every tape amplifier has at least two inputs, one for high-level sources and the other for low-level, specifically microphones. In moderate-price recorders the low-level source accommodates only high-impedance microphones, which have an impedance in the order of 5,000 to 50,000 ohms. This is no great disadvantage so long as cable length is less than 15 feet or so. Longer cables, however, have sufficient capacitance so that, in conjunction with the input capacitance of the tube, they act

as a serious shunt at frequencies in the audio range (Fig. 201).

To permit long cable runs, many microphones, particularly professional ones, are of the low-impedance variety, usually in the range of 50 to 250 ohms. These, however, have much lower voltage output than do high-impedance units and require a transformer to bring their output up to the level of the latter. The professional tape recorder usually either contains one or incorporates a socket for plugging in an accessory transformer of this kind.

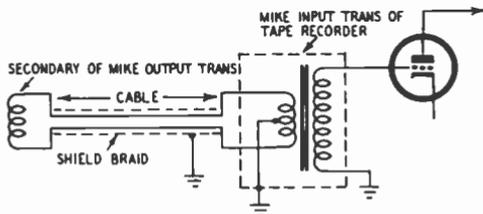


Fig. 202. *Balanced microphone-cable connection.*

Where cable runs are of substantial length, using a low-impedance microphone, the cable connection to the tape amplifier is often of the balanced type (Fig. 202) which cancels out, with respect to ground, hum and noise (fluorescent lights, static, etc.)

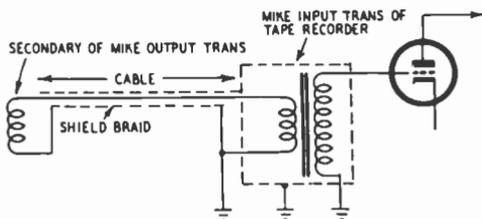


Fig. 203. *Unbalanced microphone-cable connection.*

picked up by each cable lead. Fig. 203 shows an unbalanced connection between microphone and input transformer, which is more susceptible to hum and noise pickup.

Outputs

In moderate-price tape recorders, high-impedance outputs ranging from 100,000 ohms to 1 megohm are usually the rule, resulting in high-frequency losses between the recorder and following audio equipment if more than a very few feet of cable are used. Losses occur for a reason similar to that represented in Fig. 201. Consequently, the better amplifiers provide a low-impedance

output so that fairly long cables can be used. This may be a cathode-follower output, having an impedance of several hundred ohms, which should be fed into loads of at least 10,000 ohms, and preferably 100,000. Or it may be a transformer output having an impedance of 600 ohms, which is standard in much professional audio equipment; equipment designed to accept signals from a 600-ohm source will seriously load down a high-impedance source.

Most tape recorders provide an output jack so that high-impedance headphones may be inserted for monitoring. In a tape amplifier with separate record and playback sections, the monitoring jack is placed across the regular output jack so that the monitor may hear whatever signal comes from the recorder, which may be either the incoming signal or the playback signal from the tape. In a tape recorder with a common record and playback amplifier, the monitor jack customarily is connected to a late record stage although in some cases it may also be connected across the output when the amplifier is switched to playback.

Mixing facilities

Although some tape recorders permit both a high-level (tuner, control unit, etc.) and low-level (microphone) signal to be recorded simultaneously, only the more elaborate recorders provide individual gain controls for each source. If but one gain control is available, the level must be set for microphone input and the level of the other signal must be set at the source. Ordinarily this cannot be done at the control unit because the signal level fed to the tape recorder usually (and properly) is independent of the control unit's volume control. Thus it may be necessary to add a mixer between the control unit and the tape recorder amplifier.

A-B comparison

One of the principal advantages of a tape recorder employing separate record and playback heads and separate amplifiers is that it permits immediate checking of the quality of the recording. To facilitate this check, the recorder incorporates an A-B switch which connects the output to either the incoming signal (A) or the tape playback (B). By rapid switching between the two signals, the listener can readily tell whether the recording is a reasonable facsimile of the original.

Although a switch is ordinarily used for A-B comparison,

another technique is to use a fader consisting of a potentiometer which has its center point connected to ground. On one side of center, the arm of the pot picks up the incoming signal from the record preamplifier while on the other side it picks up the playback signal. Whereas the fader gives the listener control over the level of either signal he wishes to hear, the switch permits the ear to transfer immediately from one source to the other so that the comparison is sharpened by the absence of a time interval.

Metering facilities

Every tape recorder has a means of indicating to the operator the proper record level so that he may avoid excessive distortion and yet record at a level high enough to produce a satisfactory signal-to-noise ratio. For best results a meter is considered preferable to the electron-ray-tube (magic eye) and neon-light indicators.

Where a record-level meter is employed, provision is usually made for calibrating the meter so that it accurately indicates permissible record level as determined by maximum acceptable distortion. Calibration may vary with the type of tape.

A record-level meter is customarily, though not always, used for two other purposes: measuring bias level and tape output. Correct bias setting is vital in obtaining a satisfactory combination of low distortion, high signal-to-noise ratio and wide frequency response. The meter can be used in setting bias for optimum results and is valuable as a means of speedily checking whether bias is at a level previously determined to be correct.

When the meter is used to measure the signal level recorded on the tape, this can show whether too high a recording level was employed in making the tape, thereby indicating the source of distortion, if such is discernible. Measurement of tape output can be important in setting the playback gain to provide the correct amount of signal to following audio equipment.

Alignment facilities

Seldom do moderate-price tape amplifiers permit ready adjustment of bias. If a meticulous operator does wish to adjust bias for optimum performance, it is necessary to change the value of either a resistor or capacitor. Professional and semiprofessional amplifiers incorporate a potentiometer or variable capacitor for ad-

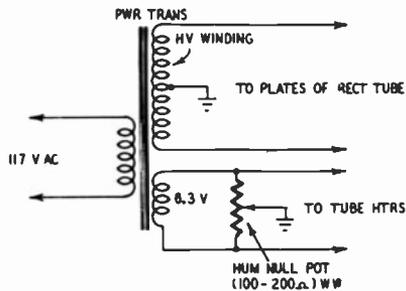
justing bias in accordance with the manufacturer's instructions.

Similarly, equalization is usually fixed in moderate-priced recorders and variable in professional ones. Adjustable record treble boost and playback bass boost permit the operator to make his machine conform to standard equalization. Sometimes, variable treble equalization is also included in playback to compensate for losses in the playback head. However, in some tape recorders the quality of the heads is such that response is quite satisfactory without compensation of playback-head losses.

When a meter is employed to measure record level, output and bias, it is desirable that facilities be included for calibrating each function. Optimum bias should correspond to a well-defined point on the meter, usually zero in the case of a VU (volume unit) meter.

If the tape amplifier has ac on the tube heaters, a hum-null potentiometer (Fig. 204) is a desirable feature. Most home recorders use ac on the heaters and to cancel hum they ground the center tap of the heater winding on the power transformer (Fig. 205). However, the center of the winding may not be the best point for balancing out hum; a potentiometer as shown in Fig. 204 can do a more effective job.

Fig. 204. Hum cancellation by use of a hum-null potentiometer.



Layout and components

However good the electronic design of a tape amplifier may be, its successful transformation into high-quality performance depends upon careful layout and use of high-quality components.

Proper layout must provide accessibility for servicing, minimize heating of vital parts and avoid hum pickup at susceptible points. Both the record and playback sections of the amplifier are high-gain circuits and stray feedback can produce oscillation, quite possibly outside the audio range. Although inaudible, oscillation can prevent proper operation of the amplifier or associated audio components. Another possible difficulty is stray pickup of bias

current. This can affect the meter indication of record level and can increase bias current supplied to the record head above the proper level.

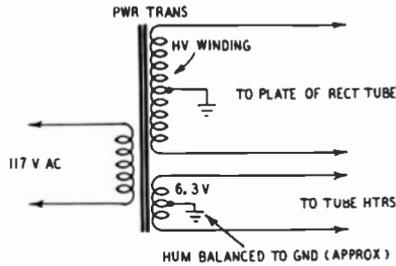


Fig. 205. Hum cancellation by grounding the heater winding.

A well-made amplifier, at a moderate increase in cost, uses resistors and capacitors overrated in terms of wattage and voltage. This not only cuts down service needs but also insures stability of operation because parts subject to overheating or excessive voltage stresses may change value or break down. Off-value components can affect bias current which in turn means affecting frequency response, distortion and signal-to-noise ratio. They can affect equalization circuits and therefore frequency response and they can affect meter calibration and signal-to-noise ratio. A high-quality amplifier uses low-noise resistors, either of the deposited-carbon or wirewound type, in early stages, which largely govern amplifier noise. Capacitors should be of good manufacture and as free as possible of leakage, and should avoid excessive departure from nominal value.

Miscellaneous mechanical features

One of the chief bugaboos of the recordist is that the tape amplifier may accidentally be in record position when it is desired to play a valued tape, resulting in accidental erasure. Two precautionary devices may be used to prevent this. One is a mechanical lockout which prevents switching the amplifier into record position without pushing or depressing an auxiliary lever or button. However, it is possible that the tape to be played may be placed on a machine which was left in the record position. Thus as a further safeguard the recorder should have a warning light that glows commandingly whenever the unit is in record position.

The amplifier should contain at least one switched ac power outlet for supplying current to the transport. One or more

additional switched outlets are desirable for supplying power to such equipment as a mixer, a second-channel amplifier for stereo purposes, etc.

Illustrative amplifiers

Fig. 206 presents front and back views of a typical high-quality tape-recorder amplifier that is used in the Concertone Series 20.

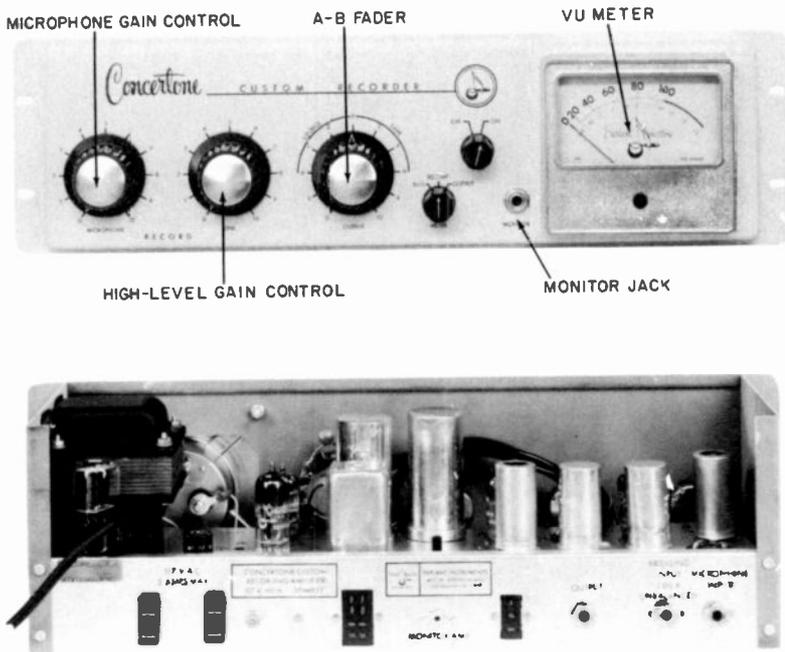


Fig. 206. Two views (front and rear) of a tape recorder amplifier. (Courtesy, American Electronics, Inc.)

On the front panel, from left to right, are the following: (1) microphone gain control; (2) line or high-level gain control; (3) A-B fader, which feeds either the incoming signal or the tape playback to the output and also determines the output level; (4) switch for employing the VU meter to measure record level, output level or bias; (5) off-on power switch; (6) monitor jack for headphones; (7) VU meter.

On the rear panel, from left to right, are: (1) two switched ac power outlets; (2) record-head jack; (3) monitor jack; (4) play-

back-head jack; (5) the output jack; (6) the line input jack; (7) microphone input jack. Above the chassis (not visible) there are: (1) a control for calibrating the meter so that it reads 100 at correct bias; (2) a pot for setting bias level; (3) a socket for plugging in an output transformer to obtain 600-ohm balanced output (center tap to ground); (4) an input transformer socket which permits feeding a low-impedance microphone into the low-level jack.

head characteristics

THE record, playback and erase heads depend upon similar fundamental magnetic principles, although the manner in which these principles are employed differs for each type of head. Moreover, heads of a given kind (as, for example, playback heads) differ in structure according to the manufacturer and various electrical considerations; consequently the design of a tape amplifier must specifically consider the heads with which it is to be used.

Underlying principles

To a relatively slight extent, magnetism occurs in nature, as in bits of magnetic iron ore. More commonly, it is man-made from developed alloys with desired magnetic properties (permanent magnets) or magnetic fields generated by electrical means (electromagnets).

Consider the magnetic field produced by a simple bar magnet



Fig. 301. Flux lines of a bar magnet.

(Fig. 301). Magnetic lines of force leave the magnet, go through the air or some other external path and return to the magnet.

Each line is a complete loop and, by convention, is said to go from south to north inside the magnetic material and from north to south outside of it. Actually, there are no individual lines, but the concept is useful in measuring the relative strength

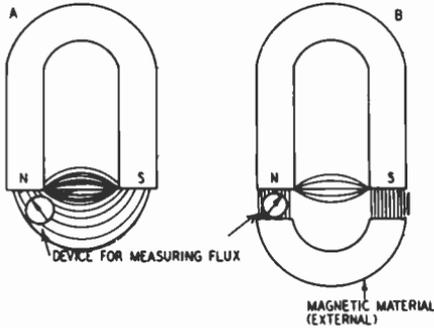


Fig. 302-a,b. Effect of a magnetic material upon the external flux lines of a horseshoe magnet.

of the magnetic field. The group of lines is referred to as magnetic flux, and flux density denotes the strength of the field.

Magnetic lines have two noteworthy characteristics: (1) they never cross each other; (2) they seek the path of least magnetic resistance (termed reluctance), which may or may not be the shortest path. A relatively few materials, such as iron and certain alloys, have low reluctance compared with air and there-

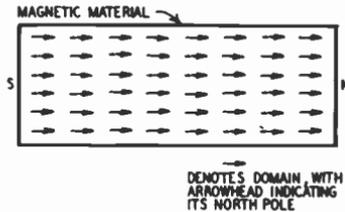


Fig. 303. Orientation of domains to form a magnet.

fore are called magnetic. Permeability is the opposite of reluctance, and so these materials have high permeability.

Fig. 302 demonstrates these two characteristics by means of a horseshoe magnet and an external magnetic material. A meter which can measure lines of force in a given area is placed at a fixed point near the north pole. In Fig. 302-a the meter reading indicates the presence of relatively few lines of force since the

flux lines must travel through air. In Fig. 302-b the external medium offers a path of much lower reluctance and the meter, being in this path, registers a much higher reading. Thus a highly permeable material when placed in a magnetic field attracts lines of force through itself.

The magnetic nature of a material is attributed to its molecular structure. A group of atoms is said to form a domain, which has magnetic properties. Some materials have domains that are magnetically very pronounced; in other materials they are magnetically ill-defined.

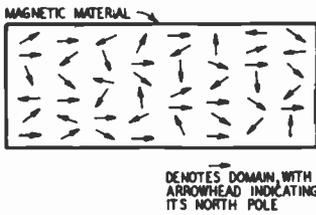


Fig. 304. Random orientation of domains, resulting in absence of magnetization.

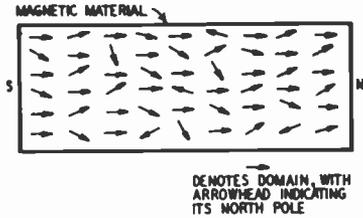


Fig. 305. Partial alignment of domains to form a magnet of moderate strength.

Each domain may be likened to an extremely small bar magnet. If all the domains are aligned substantially in the same direction, the material becomes a magnet with a south and a north pole (Fig. 303). However, if the domains are randomly oriented (Fig. 304), magnetic fields tend to cancel so that the material essentially has no magnetic poles. Between these two extremes lies the situation of Fig. 305 where many but not all of the domains are

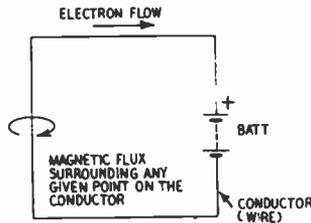


Fig. 306. Magnetic flux created by passage of an electric current through a conductor.

aligned in a common direction so that the material does have moderate magnetic properties. In other words, the more domains lined up, the stronger the magnet that is formed.

If an electric current flows through a conductor, a magnetic

field is formed around the conductor (Fig. 306). If a closed circuit (Fig. 307) consisting of one or more loops of wire is cut by a magnetic field, a voltage is induced and a current will flow in the conductor so long as the field is in motion.

Figs. 306 and 307 presume a direct current, but the same basic principles apply to an alternating current; that is, an alternating

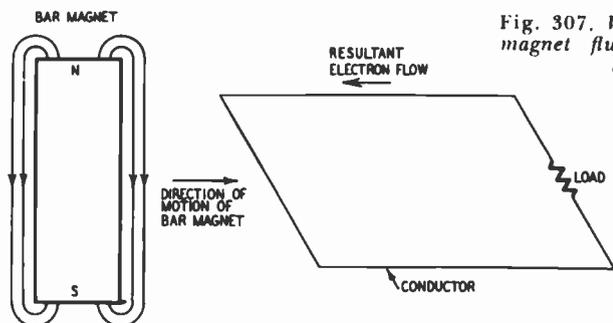


Fig. 307. Voltage induced by magnet flux cutting across a conductor.

current produces a magnetic field that is expanding and collapsing as it changes polarity. Conversely, an expanding and collapsing (changing) magnetic field induces an alternating voltage.

The requirement that the magnetic lines be moved across the wire to induce a voltage can be met in a number of ways: (1) by physically moving the magnets; (2) by having the magnetic field expand and collapse; (3) by moving the conductor in and out of the magnetic field. In any case the flux lines must move across the conductor.

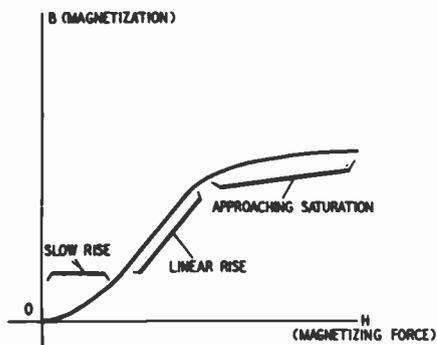


Fig. 308. Normal saturation curve of a magnetic material.

To increase the amount of wire which can be cut at a given moment by a magnetic field (thereby increasing the induced

voltage) the wire is formed into a coil. The voltage induced in the coil is directly proportional to (1) the number of turns in the coil, (2) the strength of the magnetic field, (3) the rate at which the coil is cut by the field. In the case of a magnetic field produced by current flowing through a wire, the strength of this field is proportional to (1) the number of turns and (2) the amount of current flowing. The symbol H is used to denote the intensity, or force, of the magnetic field.

For a given magnetic force H , the number of flux lines produced per unit of area in a material depends upon the permeability of the material. The letter B is used to denote the flux density per unit area. For example, between the poles of a horseshoe magnet there exists a certain magnetic force H , and the value of B at any area in a path between the poles depends upon

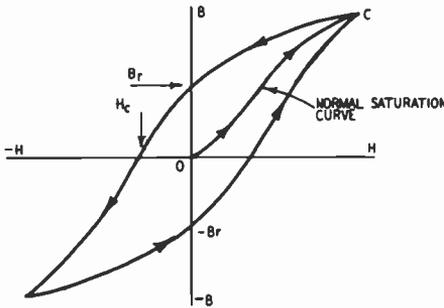


Fig. 309. *Hysteresis loop of a magnetic material.*

the material and length of the path. Thus in Fig. 302-b, B has a greater value where the meter is located than between the extremities of the poles (Fig. 302-a). The path in which the meter lies (Fig. 302-b) has less reluctance.

When a certain value of H is applied to a magnetic material in a nonmagnetized condition, the resulting value of B depends upon the particular material. Ordinarily the value of B does not increase linearly, that is, in direct proportion to H as the value of H increases from zero. In general, the increase of B is small (at first) compared with that of H , then B 's increase becomes proportional to the rise in H . Finally the increase in B again becomes quite small even though large changes occur in H . The last condition is called saturation. This sequence is represented in Fig. 308 by what is called a "normal saturation curve."

Such behavior can be explained by the theory of magnetic domains. At first the domains resist reorientation, having an inertia

analogous to that of a heavy object. Hence the initial rise of H from zero to some moderate value results in little magnetization of the magnetic material. Once their inertia has been overcome, the domains line up essentially in proportion to the increase in H . However, when nearly all the domains have been aligned, relatively large increases in H can produce only small increases in B . When *all* the domains are lined up, the material then behaves in the same manner as air: B increases only one unit for each unit

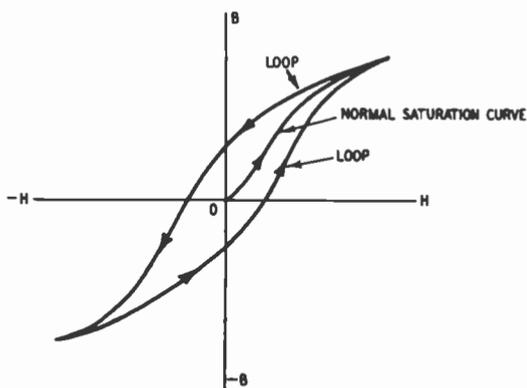


Fig. 310. Hysteresis loop of a "soft" (easily magnetized) material.

increase in H whereas, in the middle portion of the normal saturation curve, a one-unit increase in H may produce, say, a 400-unit increase in B . Practical values of B/H (termed μ or permeability) range from several hundred to several hundred thousand.

After H has increased to the point where B reaches saturation, B does not become zero when H is returned to zero (Fig. 309). Instead, B remains at some value referred to as remanent flux denoted by the symbol B_r . In other words, the material retains a degree of magnetism even though the magnetizing force is gone.

As shown in Fig. 309, to reduce B to zero, the magnetizing force must now be applied in the negative direction. The value of $-H$ required to do so is termed coercive force, symbolized by H_c . If $-H$ is increased beyond the point $-H_c$, a state of magnetic saturation will be reached as before, but in the negative direction (the poles of the material are reversed). When the magnetizing force is returned from $-H$ to zero, B remains at a value $-B_r$. Increasing the magnetic force to H_c brings B to zero. A further increase in H results once again in saturation in the positive direction. The cycle is then complete.

This cycle is termed a hysteresis loop and is important in tape recording in a number of ways. Various materials have differently

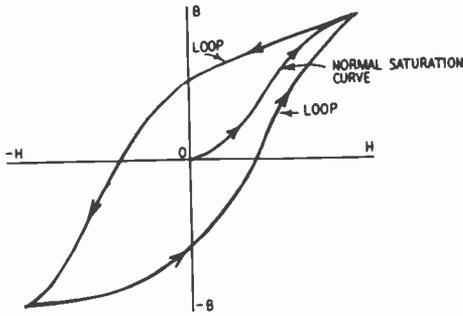


Fig. 311. Hysteresis loop of a "hard" (difficult to magnetize) material.

shaped hysteresis loops (Figs. 310 and 311). The narrow loop in Fig. 310 represents a "soft" material that is very easily magnetized and demagnetized, thus retaining very little flux when magnetic

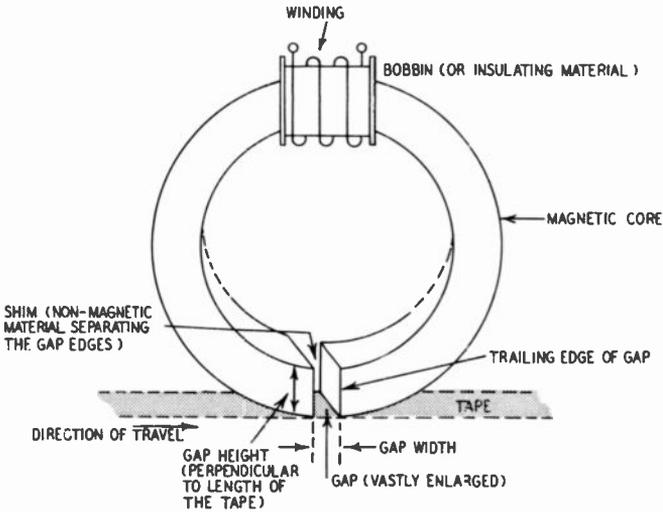


Fig. 312. Basic structure of the tape recorder head.

force is removed. The broad loop in Fig. 311 represents a magnetically "hard" material.

Structure of the heads

The basic structure of the modern head (Fig. 312) consists of three elements: a core of magnetic material providing a complete

magnetic path, a winding around the core and a gap in the core. The head is enclosed in a protective housing made in part of a magnetic material to shield the coil against hum pickup by strong magnetic fields. The head contacts the tape at the gap. The purpose of the gap is either to cause the magnetic flux in the core to enter the tape or, conversely, to cause the magnetic flux in the tape to enter the core. The winding carries a current which produces a magnetic field in the core or, conversely, an induced magnetic field in the core generates a voltage in the winding. The winding goes to the output of the record amplifier, input of the playback amplifier or the erase oscillator, depending upon the function of the particular head.

The core

The core must be of a material with high permeability, that is, easily magnetized and demagnetized. For this purpose, most heads

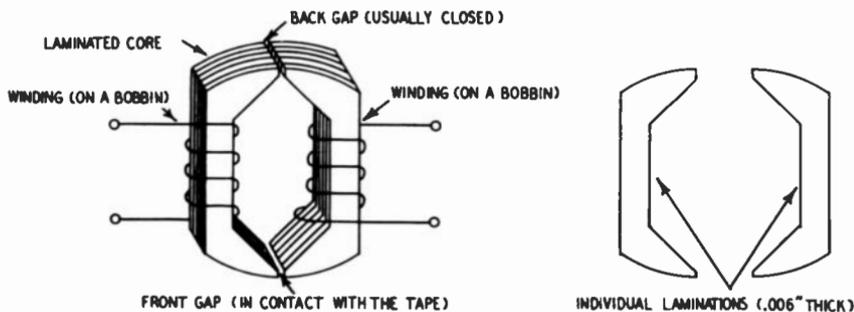


Fig. 313. Details of a laminated head.

employ an alloy such as Mumetal. Core construction is of two basic types, laminated or nonlaminated. Fig. 313 is a drawing of a laminated head. Two of the laminations are at the right and the assembled core at the left. Fig. 314 shows a nonlaminated core.

Because of its greater volume of magnetic material, hence lower reluctance, the laminated core tends to have greater output. At the same time the laminations, which are less than 0.01 inch in thickness, serve to reduce eddy current losses as compared with a solid structure. On the other hand, the nonlaminated head is less costly.

The laminated head in Fig. 313 is made up of C-shaped sections for convenience of manufacture. Usually there is a butt joint at the back of the head instead of a second gap. This decreases the

overall reluctance of the magnetic path because the flux in the core does not have to jump another gap. The nonlaminated

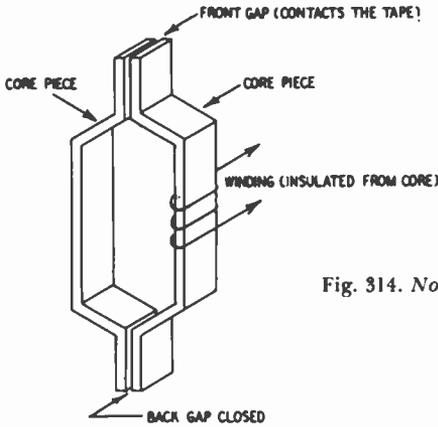


Fig. 314. Nonlaminated head showing gaps (vastly enlarged).

head can be made of two C-sections (Fig. 314) or it can be made of two sections as shown in Fig. 315. Here one of the sections

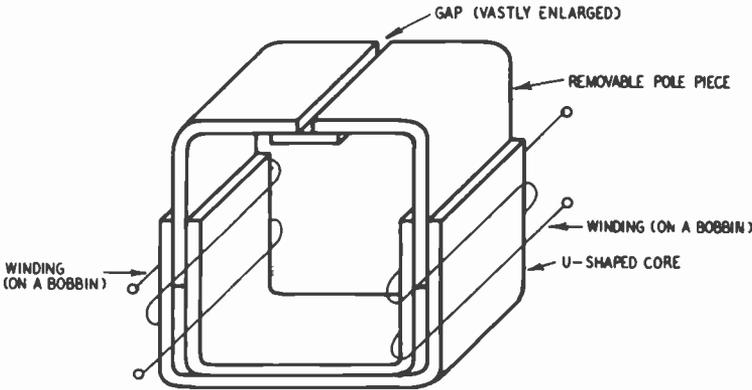


Fig. 315. Structure of a nonlaminated head with a removable pole piece.

contains the gap while the other forms a receptacle which permits the "pole piece" that contains the gap to be readily inserted or removed when the gap has worn out. The disadvantage of the head in Fig. 315 is that the gap has very little depth and therefore wears out more quickly. On the other hand, the removable pole-piece feature means that the part of the head most subject to wear can be readily replaced at moderate cost.

The winding

Most heads employ two windings, one on either side of the gap (Fig. 313), although sometimes the head (Fig. 314) employs but

a single winding. The usual method of connecting dual windings (Fig. 316) for playback is in series. This increases the voltage

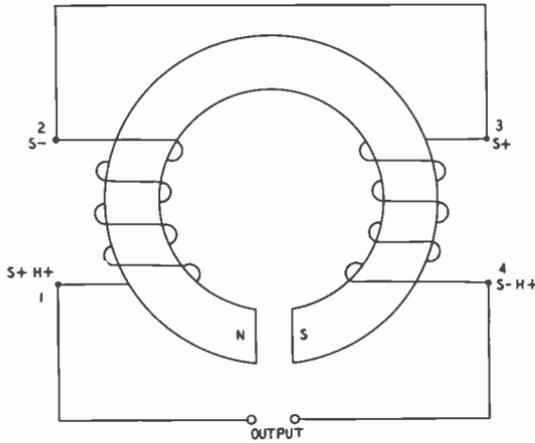


Fig. 316. Hum-bucking effect produced by series connection of dual windings. *S* denotes instantaneous signal polarity. *H* denotes instantaneous hum polarity.

output and at the same time tends to balance out hum. The hum polarity tends to be the same at the lower terminal of each coil, but signal polarity is positive for one terminal when it is negative

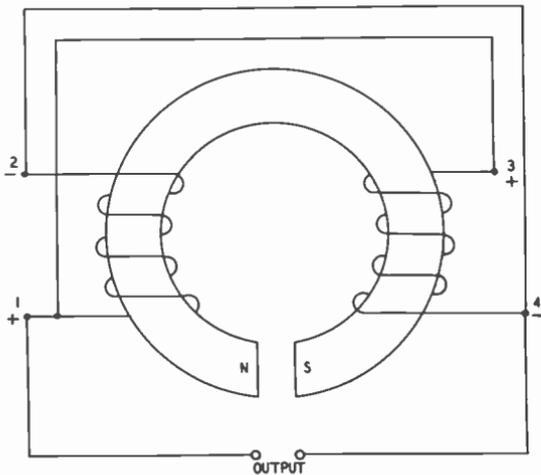


Fig. 317. Parallel connection of dual windings.

for the other (terminals 1 and 4). To the extent that hum polarity is the same at the end terminals, no hum voltage is fed to the playback amplifier.

In record and erase heads, dual windings are usually connected

in parallel to accommodate more readily the current requirements of these heads (Fig. 317). In parallel, the impedance of the windings is one-fourth that of the series connection, thereby permitting a substantially greater current flow for the same applied voltage.

The voltage output of a playback head can be raised by increasing the amount of turns, but this is practicable only up to a point. In addition to possible space limitations, the number of turns is restricted by cable, tube input and interwinding capacitances across the output of the head. Because the coil is very closewound to fit into the available space, there is a fair amount of capacitance between layers. This, in parallel with the other capacitances, acts as a shunt at high frequencies.

Fig. 318 is the equivalent circuit of the playback head together with the stray capacitance. The generator represents the voltage induced in the playback head by the magnetic field on the tape.

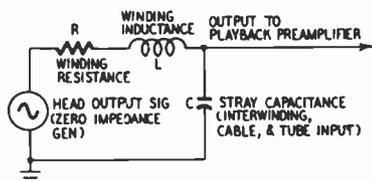


Fig. 318. Effect of capacitance upon playback-head output.

This circuit behaves as a low-pass filter, attenuating frequencies above that where the head winding inductance L and stray capacitance C resonate. The resonant frequency of the head must be kept above the audio range to avoid undue treble losses.

Heads specifically designed for recording (and also erase heads) have fewer turns in order to present less impedance to the required current flow. Therefore interwinding and other forms of stray capacitance are not a problem at *audio* frequencies. However, at the bias frequency, which commonly ranges from 30,000 to 100,000 cycles, stray capacitance must be kept low enough so that the record (and erase) head is self-resonant at a point at least as high as the bias oscillator frequency. If the resonant frequency were identical to the oscillator frequency, a maximum amount of current would circulate in the resonant circuit (which includes the winding) thereby reducing the voltage required from the oscillator to a minimum. However, this mode of operation is ordinarily too critical for practical use.

For the most part, the record heads used in home tape recorders have a relatively high impedance (chiefly inductive reactance—

that is, more turns) whereas in professional machines there is a tendency to use heads of lower impedance. One of the principal advantages of low-impedance record heads is that they not only have much less interwinding capacitance but are also less affected in the audio range or at the bias oscillator frequency by stray capacitance. This permits relatively long runs of cable (on the order of feet rather than inches) between the head and the tape amplifier without unusually significant treble losses. Another advantage is that to produce the same amount of bias magnetic field (ampere turns) less voltage is needed because it is easier for the current to flow through a low-inductance (low-impedance) winding. And the smaller the bias voltage, the less chance there is of stray bias radiation affecting other circuits, such as the record-level indicator. Bias frequencies, particularly in professional machines, are high enough to display a fair amount of radio-frequency characteristics.

The chief disadvantage (low signal voltage) of a low-impedance winding occurs in the playback head. If a satisfactory signal-to-noise ratio is to be had, a stepup transformer must be used between the head and the tape amplifier. However, the transformer has its own high-frequency losses, due to leakage inductance and interwinding capacitance, which act in a manner similar to that shown in Fig. 318. Since even a low-impedance head has some effective capacitance to ground, there are now two sources of high-frequency loss; one in the head and one in the transformer (Fig. 319). Moreover, every inductance is susceptible to hum pickup, and the use of a stepup transformer, particularly at a very low-level stage, is a potential source of hum.

The gap

Gap width, often misleadingly called gap length (Fig. 312), is a critical factor in the playback head. The narrower the gap, the higher the frequency range of the playback head at a given tape speed. For a given gap width treble response varies directly with tape speed.

Modern audio playback heads (or record-playback heads) seldom have a gap wider than 0.0005 inch. The gap in high-quality heads is generally about 0.00025 inch wide, and there are some commercial heads with gaps as narrow as 0.00020 and 0.00015 inch. Little would be gained by narrowing the gap further to reduce playback losses at low speeds because present-day recording losses at these lower speeds are so large that it is impractical

to compensate for them over the entire audio range. Also, if the gap is reduced, the output of the playback head tends to decrease. The magnetic flux in the tape tries to take a path not only through the core but also right across the gap if the opposing faces are close enough. To the extent that the magnetic flux does not travel through the core, a smaller voltage is induced in the winding of the playback head.

In the record head, if a separate one is used, gap width is not a critical factor and is generally below 0.001 inch. In many cases, the same type of head is used for record and playback on a three-head machine and in this event the gap dimension is, of course, the same as that of the playback head.¹ Recording takes place at the trailing edge of the gap (Fig. 312). Therefore a critical factor is the definition of the gap—that is, the sharpness and linearity of the edge. At the moment the tape leaves the gap, the signal is recorded on the tape, and if the gap edge is not sharply defined, neither is the signal.

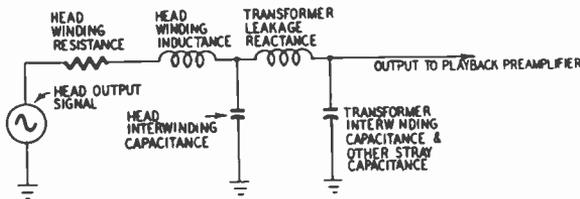


Fig. 319. Combined effects of playback-head and transformer losses upon output.

Sharpness of the gap edge is also important in the playback head. To the extent that the edge is rounded, the gap behaves magnetically as though its width were increased. Inasmuch as it is practically impossible to create a perfectly straight edge, magnetic gap width is always somewhat greater than physical gap width. This is also partly due to various electrical effects, such as eddy currents and gap-edge saturation, which tend to blur the edges magnetically. In a well-made head, the magnetic gap exceeds the physical gap by no more than about 10%.

In the erase head, a relatively wide gap is required, usually upward of 0.005 inch, so that the magnetic flux emanating from the gap can span a substantial portion of the tape and therefore penetrate it adequately.

¹ Sometimes heads that do not meet the exacting requirements for playback are classified by the manufacturer as record heads, for which they can be perfectly suitable.

Operation of the heads

While the record, playback and erase heads are very similar in physical appearance and internal structure, each one operates in a very distinct manner.

Record head

The record amplifier supplies a current to the winding of the record head. Except for frequency equalization, this current corresponds to the incoming audio signal (microphone, tuner, etc.). To this is added a bias current ordinarily having a frequency between 30,000 and 100,000 cycles, to decrease distortion and increase output. The current through the winding produces a magnetic flux in the core. Since the tape bridges the gap in the core and has a much lower reluctance than the gap, the flux flows from one edge of the gap into the tape and from the tape back into the core through the other side of the gap, thereby magnetiz-

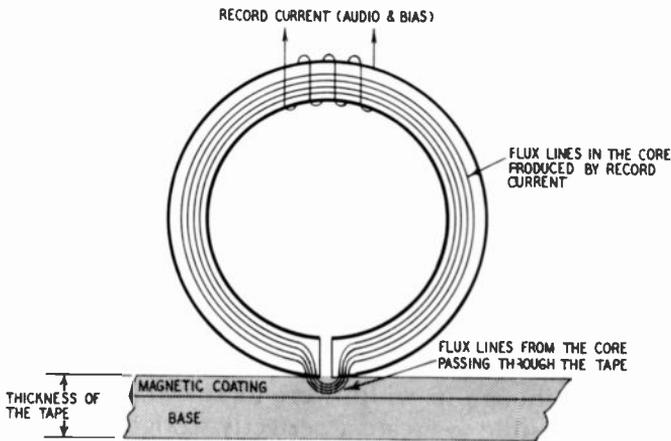


Fig. 320. Operation of the record head.

ing the tape (Fig. 320). Magnetization continues until the moment the tape leaves the trailing edge of the gap. The magnetization that is left on the tape is determined by the magnetic conditions existing at this edge.

The amount of audio current required to drive the record head without resulting in excessive distortion of the recorded signal varies considerably with head construction. However, it is possible to give an idea of the magnitude of this current. High-impedance heads generally require from about 0.02 to 0.08 ma of

audio current, low-impedance heads from about 0.2 to 1 ma.

The bias requirement of the record head is roughly 10 times the maximum permissible audio record current, although in some cases it is appreciably higher or lower than this. Generally, where high-impedance heads are employed, the appropriate bias current is in the vicinity of 1 ma. Low-impedance heads, however, may require amounts up to 10 ma or so.

The extent to which the record head produces a magnetic flux is directly proportional to the amount of current flowing through the winding. Thus the head is termed a constant-current device: constant flux output at all frequencies for constant current.

However, the head winding has inductance. Except at the very lowest audio frequencies, the inductive reactance of the winding is considerably greater than its ac resistance. Thus, the impedance of the head rises with frequency throughout the audio range. A rising impedance restricts the flow of current through the coil, resulting in discrimination against high frequencies. It is necessary that the record amplifier be designed so that the amount of current through the winding is not affected by the rising imped-

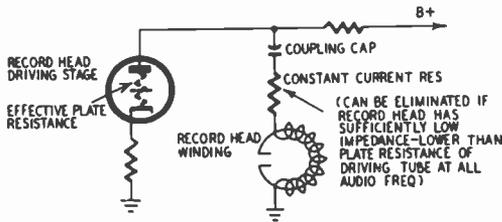


Fig. 321. Use of a constant-current "swamping" resistor to drive the record head.

ance of the coil. This is accomplished by feeding the signal to the record head through a resistance substantially greater than the impedance of the head at all audio frequencies. Therefore the amount of current through the complete circuit, including the head, is basically determined by the series resistance. This "swamping" resistance may consist of an actual resistor between the head and the plate of the "driving" tube (Fig. 321). Or, where a low-impedance record head is used, the plate resistance of the driving tube may be sufficient.

The record and erase heads exhibit so-called iron losses which increase with frequency. These are of two types, hysteresis and eddy current losses. The nature of hysteresis losses can be explained by referring to the hysteresis loops of Figs. 309, 310 and 311. The area

within the hysteresis loop is proportional to the energy required to magnetize a given material, in this case the core of the head. Energy must come from somewhere, and in the record head it comes from the current in the winding. The energy, dissipated as heat within the core, is referred to as hysteresis loss. Inasmuch as the winding of the head carries alternating current (that is, the audio and bias signals), the number of hysteresis loops per second and therefore the amount of energy dissipated per second varies with frequency. Thus, assuming constant flux magnetization, hysteresis losses increase in proportion to frequency.

Fig. 322 helps explain eddy-current losses and how they may be reduced. When the record head produces an alternating magnetic field in response to the current flow through the winding, this field cuts through the core itself. Since the core is an electrical conductor, small voltages are induced in it. The core can be considered as consisting of a large number of rings concentric to the axis of the core and electrically in parallel with each other, as shown at the left in Fig. 322. The changing magnetic field cuts into each of these elemental rings and induces a minute voltage in it. This voltage causes current to flow, the amount depending upon the resistance of the elemental ring. Current flowing through a resistor represents energy, which is dissipated within the core as heat. The energy comes from the current in the winding. The currents induced in the elemental rings are called eddy currents and the consequent dissipation of power is an eddy-current loss which increases with frequency.

To minimize eddy-current losses, the structure of many heads consists of laminated sections. Thus, the continuity of the elemental rings tends to be broken up, as shown at the right in Fig. 322 (and also in Fig. 313) limiting the flow of eddy currents.

Hysteresis and eddy-current losses also occur in the playback and erase heads and need not be described further, except to say that in the erase head the heating effect sometimes causes it to become sufficiently hot to damage the tape if at rest against the head.

Playback head

Because of the low reluctance of the core, the magnetic flux in the tape seeks to complete its external path through the core. The flux enters the core through the gap and, in going through the core, induces a voltage in the winding surrounding the core. This voltage is fed to the input of the playback amplifier. The situation is just the converse of Fig. 320. Now, instead, the flux

originates in the tape, with the audio signal leaving the winding instead of entering it.

For a voltage to be induced in a coil by a magnetic field, the field must be continuously cutting across the coil. The playback head must therefore be confronted with a tape which bears a magnetic flux constantly changing in value. This requirement is of course met by the sine wave, the basic component of audio signals.

The playback head conforms to the principle that the voltage induced in a coil by a magnetic field varies directly with

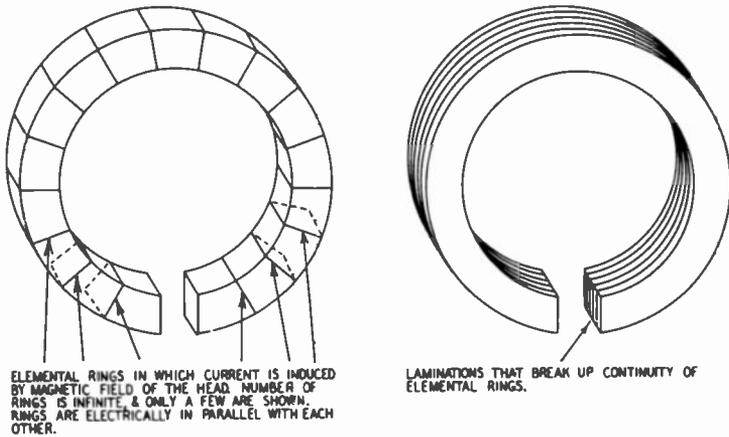


Fig. 322. Cause and reduction of eddy-current losses.

the rate at which the magnetic field changes. Thus, assuming that at all audio frequencies signals of equal strength (flux) have been recorded on a tape, the higher the frequency the higher will be the voltage output, within certain limits. Thus, doubling the frequency doubles the induced voltage, and so the output of the playback head essentially rises with frequency at the rate of 6 db per octave (2 to 1 voltage ratio for a 2 to 1 frequency ratio), until upper frequency limits are reached.

Lest there be any misunderstanding, note that output of the playback head depends not only upon the frequency recorded on the tape but also upon the recorded magnitude (flux density). In other words, the rate of change of the magnetic field is determined by two factors: (1) frequency of change (times per second); (2) amount of change between maximum and minimum values of flux.

The term velocity may be used to refer to the rate of change

of the magnetic field. Inasmuch as the output of the playback head varies directly with velocity (except for various losses at the treble end), the head is referred to as a constant-velocity device: constant output at all frequencies for constant velocity (rate of change of magnetic field).

Fig. 323 shows the theoretical response of an "ideal" playback head (no treble losses except those due to gap width), assuming

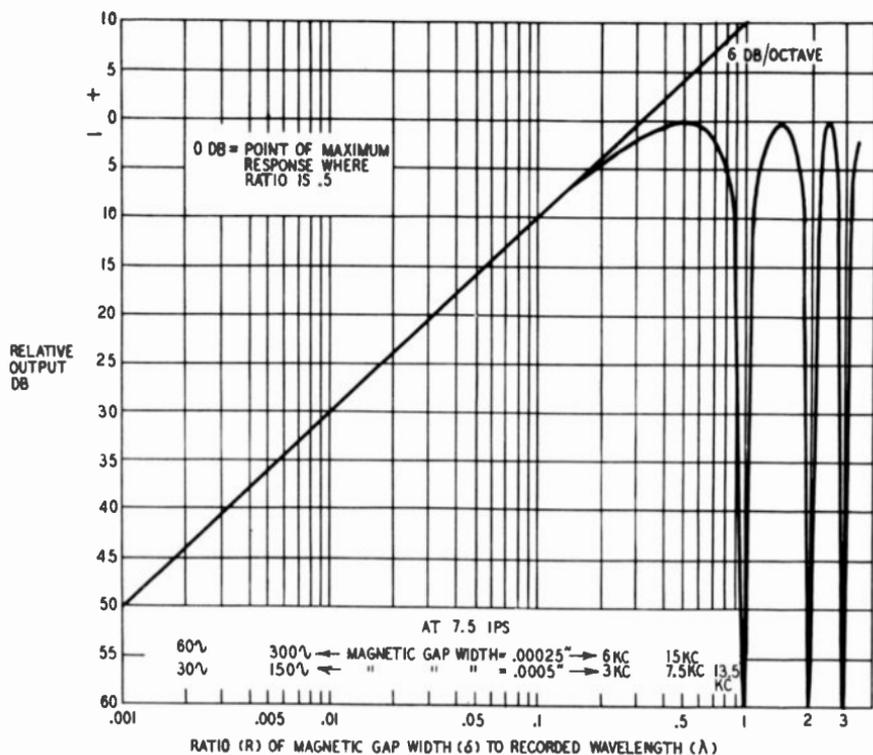


Fig. 323. Theoretical response of an "ideal" playback head, assuming equal recorded flux density on the tape at all audio frequencies.

equal recorded flux density on the tape at all audio frequencies. Output at first conforms to the 6-db-per-octave rise. But response eventually falls off to an extreme depth, rises again, falls and *theoretically* continues to exhibit alternate rises and falls. It is here that gap width comes into prominence, explaining this behavior.

A continuously changing magnetic flux on the tape is not sufficient to induce a voltage in the coil of the playback head. The tape flux can enter the core and thereby induce a voltage in the

coil only when there exists a difference between the magnetic intensity at each edge of the gap. This magnetic potential, as it is called, may be caused by the fact that the gap edges ride on portions of the tape which, though of the same magnetic polarity, are of different intensity, or which are of the same flux intensity but different polarity, or which are of both different polarity and intensity. In any case, the gap is confronted by a magnetic potential, thus giving the core, in effect, a north and a south pole at the instants in question. As the tape moves, the potential confronting the gap changes and thus the flux through the core changes. Therefore, a voltage is induced in the coil.

This may be clarified by referring to Fig. 324. A sine wave recorded on tape is equivalent to a series of bar magnets. Each bar

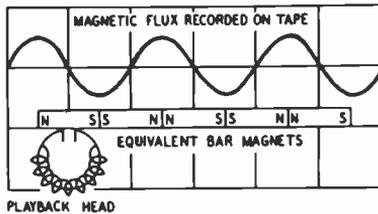


Fig. 324. Equivalent bar magnets produced by a sine wave recorded on tape.

corresponds to half of a sine wave and has a north and a south pole. As shown in Fig. 324, at a given instant the gap edges of the playback head ride on points of different field intensity. As the tape moves, the magnetic potential across the gap changes; hence a voltage is induced in the head.

The higher the recorded frequency, the shorter the bar magnet recorded on the tape; that is, a high frequency produces more but shorter bar magnets on the length of the tape that travels past the head in a given period of time, say a second. When the gap of the playback head scans a long wavelength, there is relatively little magnetic potential across the gap because the distance between the gap edges is small compared with the length of the bar magnet.

As the frequency rises and recorded wavelength decreases, the distance across the gap corresponds to a great magnetic potential. The point at which the greatest magnetic potential can be scanned by the gap occurs where the magnetic gap is equal to exactly half a wavelength. On the other hand, when the gap equals a full wavelength, it theoretically produces no output at all. This is

shown in Fig. 323, where the maximum output occurs at the point where the ratio between the magnetic gap width and recorded wavelength is 0.5. The output theoretically falls to zero when the ratio is 1. Three recorded wavelengths are shown in Fig. 325 in the form of sine waves; the first (A) is shown as being four times the width of the gap, the second (B) is equal to twice the gap width and the third (C) equals the gap. All wavelengths, or frequencies, are assumed to have been recorded with equal strength on the tape. In the case of wavelength B there are

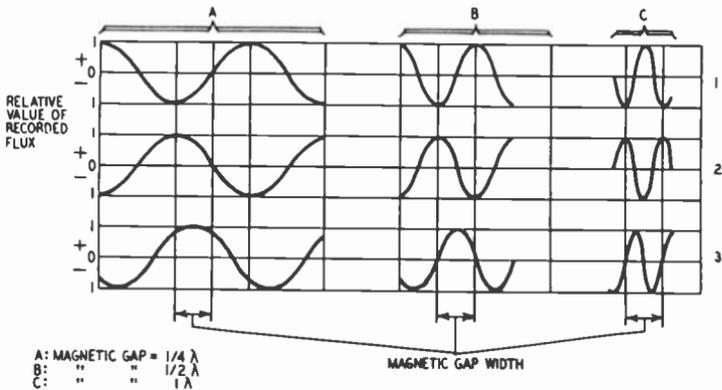


Fig. 325. Magnetic potentials scanned by a playback head for three wavelengths (A, B, C) at different phases (1, 2, 3).

instants when the magnetic potential across the gap corresponds to the difference between the positive and negative peaks of the wave. This is the largest potential that can exist. Therefore, maximum output occurs for wavelength B. In the case of wavelength A, maximum potential (row 2) is only half as great as for wavelength A. Therefore, the output can be only half as great. Turning to C, it can be seen that at all times there is a zero magnetic potential across the gap. Consequently no magnetic flux can enter the core and no output voltage can result.

Returning to Fig. 323, the theoretical response of a playback head is basically expressed there in terms of the ratio R of magnetic gap width δ to recorded wavelength λ . (If only the physical gap width given by the manufacturer is available, the magnetic width can be approximated by taking 110% of the former value.) The ratio R can be converted to frequency by the formula $f = R \times \frac{S}{\delta}$, where f is the frequency in cycles per second, S the tape speed in inches per second and δ the magnetic gap width in

fractions of an inch. For a head with a magnetic gap of 0.0005 inch, maximum output at 7.5 ips corresponds to 7,500 cycles.

$$f = \frac{S}{\lambda} = \frac{S}{\delta} \times \frac{\delta}{\lambda} \text{ but } \frac{\delta}{\lambda} = R:$$

$$\text{therefore } f = R \times \frac{S}{\delta}.$$

That is:

$$f = R \times \frac{S}{\delta} = 0.5 \times \frac{7.5}{0.0005} = 7,500 \text{ cps.}$$

Similarly, maximum output for a 0.00025-inch head is found to occur at 15,000 cycles. To find the ratio in Fig. 323 which corresponds to a given frequency, this formula is rearranged:

$$R = f \times \frac{\delta}{S}.$$

Assume the desired frequency is 7,000 cps, the gap is 0.0005 inch and tape speed is 3.75 ips.

$$R = f \times \frac{\delta}{S} = 7,000 \times \frac{0.0005}{3.75} = 0.93.$$

Fig. 323 shows that a ratio of 0.93 corresponds to playback losses so great that the response to 7,000 cycles at 3.75 ips is not practical for the head in question.²

The output, after reaching its first maximum, theoretically rises and falls between successive maximums (Fig. 323). Each maximum corresponds to 3, 5, 7 and further odd multiples of half a wavelength, while minimums correspond to 1, 2 and further multiples of a full wavelength. This area of operation, however, is of no concern to tape recorders used for audio reproduction.

In theory, the successive drops represent zero output, while the successive rises reach the same level as the first maximum, assuming equal recorded flux density at all frequencies. But, in practice, the first drop does not reach zero and the rises attain successively lower peaks. For example, in an actual head (Fig. 326) with a magnetic gap width of 0.00028 inch (physical gap width of 0.00025 inch) and operated at 7.5 ips, the output reaches a maximum at 13.5 kc, drops about 35 db at 27 kc and rises to a peak about 20 db below the maximum. Thereafter very little output is obtained.

² Mathematically, the output in Fig. 323 is proportional to $\sin\left(\frac{\pi\delta}{\lambda}\right)$: (π equals 180°). Thus, assigning an arbitrary value to a very low frequency, say 20 cycles, relative theoretical output at all higher frequencies can be calculated by remembering that δ is magnetic gap width and λ (wavelength) equals tape speed divided by frequency.

Generally, the useful frequency limit of a playback head may be approximated by the formula $f = \frac{S}{2G}$, where f is frequency, S is tape speed and G is the physical width of the gap. Maximum response occurs when the magnetic gap is equal to one-half the recorded wavelength, that is, when $\delta = \frac{\lambda}{2}$. Since the magnetic and physical gap widths of a good head differ by a factor of only about 10% and since we are dealing with an approximation, G may be substituted for δ , so that $G \cong \frac{\lambda}{2}$. Transposing, $\lambda \cong 2G$. The recorded wavelength, by definition, equals tape speed divided by frequency, or $\lambda = \frac{S}{f}$. Transposing, $f = \frac{S}{\lambda}$. Substituting $2G$ for λ , $f = \frac{S}{2G}$.

Fig. 323 shows that, at the frequency of maximum response, the playback-head output is 4 db less than if the response had followed the 6-db-per-octave line all the way. Actually, the frequency of maximum response is slightly lower than that given by the formula $f = \frac{S}{2G}$, because the magnetic gap width (δ) is somewhat greater than G . However, Fig. 323 shows that, if the ratio of magnetic gap width to recorded wavelength is as high as 0.6, the deviation from the 6-db-per-octave response curve is still only about 6 db. A ratio of 0.6 compared to 0.5 is equivalent to a deviation of 20% between the physical gap and magnetic gap widths, whereas, for a well-constructed head, the deviation is closer to 10%. Thus, the formula $f = \frac{S}{2G}$ fairly well indicates the extent of useful response, which may be considered as response no more than 6 db down from flat. In some tape recorders, provision is made for a moderate amount of treble boost in playback to compensate for the deviation of playback-head response from the 6-db-per-octave characteristic. On the other hand, such treble boost cannot be used to compensate for heads with excessively wide gaps in view of the extremely sharp drop in response soon after the ratio between gap width and recorded wavelength reaches 0.6.

Dual-purpose heads

A head suitable for playback can also be used for record, as is done in virtually all moderate-price home machines. However, if a playback head does not have to double as a record device, its

design can be altered so that it operates more efficiently than a dual-purpose unit. The principal difference is that a head intended solely for playback can be wound with a greater number of turns, resulting in higher output. But the greater inductance of such a head means a lower resonant frequency. The bias current, which is usually in the range from about 30,000 to 100,000 cycles, will be shunted to ground if resonance occurs appreciably below the bias frequency.

Output of the playback head is of relatively very low order. For a high-impedance head for both record and playback, maximum output is some 5 to 10 mv. A low-impedance head produces considerably less voltage, requiring a transformer to step it up to the level required by the tape amplifier. A high-output head designed for playback only produces a maximum output of 10 to 20 mv.

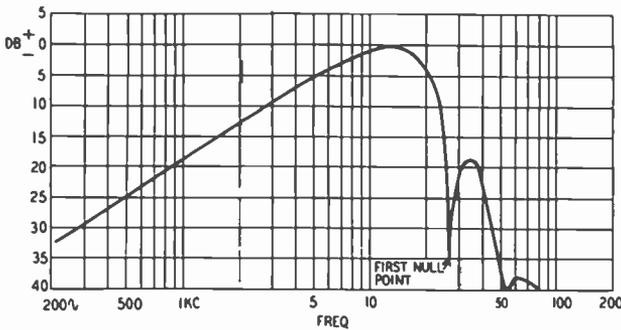


Fig. 326. Effect of gap width upon output of a high-quality record-playback head at 7.5 ips. (Source: Otto Kornei, "Structure and Performances of Magnetic Transducer Heads," *Journal of the Audio Engineering Society*, July, 1953.)

Contour and wrap effects

In the same manner that the response of a head departs from a 6-db-per-octave line at the high end, it tends to do so also at the low end. This is due to what are known as the contour effect and the wrap effect.

At very low frequencies, where a recorded wavelength approaches the lateral dimension of the head, the head as a whole tends to react to the magnetic flux on the tape. This is the contour effect. Depending on the wavelength, the reaction of the head as a whole together with the reaction of the gap may result in output voltages that are additive or partially cancelling, resulting in irregularity of response at the low end. However, by proper design of the shape of the core, this irregularity can be reduced to

negligible proportions above 20 cycles or so. In some heads, furthermore, the net result of the contour effect is a slight increase in output at the low end relative to the 6-db-per-octave response characteristic.

The wrap effect concerns the angle at which the tape approaches the head. When the tape approaches at an angle such that it contacts a large area of the playback head, the material of the head may impair the magnetic coupling between the tape and the gap at very low frequencies, where the flux extends a relatively considerable distance from the tape. This can produce a loss in response below 50 cycles. The wrap and contour effects are somewhat interdependent in that the wrap angle has an influence upon the contour effect: the greater the angle (the more of the tape that contacts the head), the greater is the contour effect.

From the point of view of reducing contour effect, it is desirable to have a head physically large compared with the recorded wavelength. On the other hand, the larger the head, the more susceptible it is to hum pickup and to wrap effect. Thus, the size of a particular head partly reflects the manufacturer's judgment concerning the best compromise among the conflicting factors.

Erase head

The erase head of the unit performs its function by subjecting the tape to an alternating magnetic field. This destroys the previously existing magnetic pattern and leaves in its place little or no magnetization, depending upon the effectiveness of the head.

The field of the erase head first saturates the tape, destroying the magnetic pattern that corresponds to a recorded signal. At this point the tape is in a highly magnetized condition as the result of the saturating field. Demagnetization of the tape takes place as it recedes from the head, being subjected to a magnetic field which is rapidly alternating in polarity and at the same time *gradually* decreasing in strength.

Fig. 327 illustrates what happens to a given particle of the tape as it goes past the erase head. The horizontal axis represents a magnetizing force H and the vertical axis the magnetic flux density B on the tape. Point *a* shows the particle in a highly magnetized state as the result of coming under the influence of the erase head's magnetic field. As the magnetizing force H returns to zero, the magnetic flux of the particle does not return to zero due to hysteresis. When H changes polarity and goes to point *b*, the particle is magnetized to saturation again but this time has

opposite magnetic polarity. H changes in polarity again, but now becomes weaker as the tape begins to leave the magnetic field of the head so that the particle's magnetization corresponds to point c . The flux of the tape particle is alternately returned to points d , e , f , g , etc., until its magnetization eventually approaches zero.

The erase head is driven by a current which, depending upon construction of the head, may vary from as little as 5 ma to as high as 300. In most home recorders the general range is in the order of 10 to 50 ma. Usually the erase frequency is upward of 30,000 cycles, being derived from the same oscillator that supplies bias to the record head. Occasionally, 60-cycle current is used to power the erase head, but results are not as satisfactory and hum tends to be recorded on the tape.

Erase heads frequently do not accomplish perfect erasure. When 100% erasure is desired, it is often necessary to use a bulk eraser, which is simply a good-sized (several pounds) electromagnet powered by the 60-cycle 117-volt line. Its field is strong enough so that an entire reel of tape can be erased in a matter of seconds by bringing the reel to the eraser and very slowly with-

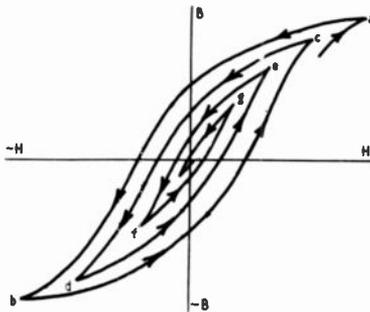


Fig. 327. Behavior of a magnetic particle in the tape during the ac erase process.

drawing it, meanwhile describing a circular movement so that all parts are equally exposed to the magnetic field.

An erase head usually becomes somewhat less effective as the erase frequency goes up. To maintain the same degree of erasure, more current and higher voltage are required with increasing frequency. The voltage requirements rise very rapidly due to the rising impedance of the head at higher frequencies.

Not all tape recorders employ an electromagnetic erase head. A few of the less expensive machines use permanent magnets. For satisfactory results, it is necessary to use a series of two or three

magnets (incorporated in one housing) which alternately differ in polarity and are so oriented with respect to the tape as to present decreasing fields. In this manner, the requirements of a magnetic field that is changing polarity and decreasing in strength are met. In another form, a permanent magnet runs diagonally from the lower to the upper edge of the track, thus subjecting each particle of the track to a magnetic field changing in strength and polarity. However, permanent magnets present problems in that erasure is generally less effective, orientation of the magnets with respect to the tape is critical and the magnet must be mechanically positioned away from the tape when the recorder is in the playback mode.

Azimuth alignment

Azimuth refers to the orientation of the head gap with respect to the tape. Correct azimuth alignment places the gap height (Fig. 312) perfectly perpendicular to the longitudinal dimension of the tape. When the record and playback heads differ in their alignment, very substantial high-frequency losses take place. If both contain exactly the same error (and this includes the case where a single head is used for both record and playback), then there is no loss as long as the only tapes played are those made on the same machine. If a tape made on a machine with correct record-head alignment is played on a machine with incorrect playback-head alignment, high-frequency response suffers. Similarly a tape made with a record head improperly aligned will play back poorly on a properly aligned machine.

Fig. 328 shows the losses that occur at 7,500 cycles at a tape speed of 7.5 ips (0.001-inch wavelength) as alignment of the playback head varies with respect to the record head. Data are shown for full-track and half-track heads. In a half-track head, misalignment of only 30 minutes of 1° reduces output more than 17 db. In a full-track head, attenuation is much greater; the same 17-db loss results when misalignment is about 12 minutes of 1° . As the alignment error is increased, the response, at a given frequency, rises again to what is known as a "false peak." Thus, in the process of azimuth alignment it is necessary to beware of the false peaks and align for the true peak, which is considerably higher.

Although a playback head may be perfectly aligned, losses can take place if the tape does not maintain a position perpendicular to the gap as it passes the head, but instead weaves so that the angle of the tape relative to the gap changes. This weaving, or

skewing, motion may be due to faults in tape guides and tension devices or wrinkled tape.

Azimuth misalignment losses

Losses due to improper azimuth alignment, especially at high frequencies, can be explained easily. If the tape is played back by a head with exactly the same azimuth alignment as the record head, then at any given instant in playback all points of the left edge of the gap are in contact with the same field intensity on the

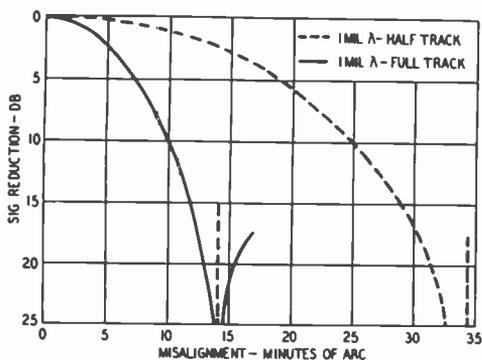


Fig. 328. Reduction in high-frequency response due to azimuth misalignment. (Source: The 3M Co., Sound Talk, Bulletin No. 27.)

tape; the same is true for the right edge. But if the playback head azimuth is slightly incorrect, then at a given instant different flux densities will be contacted by various points along the left edge. At high frequencies, where recorded magnetic poles are close together, the inclined gap edge may contact poles of different polarity which have a cancelling effect upon each other. Thus the left edge of the gap often rides on a *net* flux density considerably smaller than if all points of the edge contacted the same intensity. The right edge is at a reduced intensity in the same way. The total result of reduced field intensity at each side of the gap is a smaller potential *across* the gap and hence a lowered output.

In Fig. 328, a full-track head produces considerably greater losses than a half-track head for a given degree of azimuth misadjustment. Assume that the center point of one edge of the gap rests on a north pole, which essentially determines the polarity of this edge. However, as the height of the gap is increased, the portions of the edge above and below the center point reach out

to poles of south polarity. This tends to cancel the polarity of the central portion. In other words, each edge of a half-track gap will not extend beyond a field of given polarity as far as the edges of a full-track head.

tape characteristics

TAPE consists of a magnetic coating bonded to a base of some plastic. The coating contains a tremendous number of minute “domains,” each of which behaves like a bar magnet.

Recording and playback processes

When the tape is in an unmagnetized condition, the domains point in random directions. Their magnetic fields cancel and there is very little net magnetic flux on the tape. When subjected to the magnetic flux emanating from the record head, the domains align themselves in accordance with the polarity of the head flux. In short, the tape becomes magnetized. The amount of audio current through the record head, and thus the strength of the head’s magnetic field, determines the number of domains that become aligned in a given direction at any instant (or point on the tape). If the current is great enough, all the domains are aligned. The tape is saturated in the sense that further increases in audio current do not produce proportionate increases in the tape’s magnetization. Obviously, saturation results in distortion inasmuch as the signal recorded on the tape cannot correspond to the signal entering the record head.

In playback, the magnetic flux produced by the aligned domains enters the gap of the playback head and passes through its core, thereby inducing a voltage in the winding. This happens provided the magnetic flux is a changing one and the playback gap is small compared with the length of the flux field (wavelength) on the tape.

The use of an alternating “bias” current is of fundamental importance to the recording process. The bias current is fed into the

record head simultaneously with the audio current to accomplish two things: (1) reduce to an acceptably low level the distortion that occurs; (2) raise the level of the recorded signal; otherwise a relatively tremendous output of magnetic flux from the record head would be required to put a useful amount of signal on the tape.

Demagnetization

A phenomenon of vital importance that occurs during recording—varying somewhat among brands and kinds of tape—is demagnetization. This is one of the principal factors responsible for the high-frequency losses that take place in the recording process.

A sine wave recorded on tape is equivalent to a series of bar magnets. Each magnet equals half of a wave; one pole corresponds to the upper peak of the wave and the other pole to the lower peak; from peak to peak is half a cycle. As the audio frequency increases, the number of bar magnets formed on a given length of tape increases. For example, at a frequency of 750 cycles per second and a tape speed of 7.5 ips, the wavelength of 1 cycle in inches is $7.5/750$, or 0.01 inch. In other words, there are 100 wavelengths per inch, which means 200 magnets, each 0.005 inch long. But at a higher frequency of 7,500 cycles and a tape speed of 7.5 ips, the wavelength of 1 cycle in inches is $7.5/7,500$, or 0.001. In other words, there are 1,000 wavelengths per inch, which means 2,000 bar magnets, each 0.0005 inch long. As a bar magnet becomes shorter, magnetic strength decreases because the opposite poles tend to cancel; the closer the poles are to each other, the greater the cancellation. This is the demagnetization effect.

Therefore, in magnetic recording, as the frequency increases, the amount of magnetic flux *recorded* on the tape decreases although the strength of the magnetic flux *applied* to the tape by the record head remains the same.

On the other hand, in playback, the core of the playback head acts as a sort of magnetic “keeper” at the shorter wavelengths, serving to neutralize opposite poles and thereby tending to eliminate the cancelling effect. This restores, somewhat, high-frequency output. However, such restoration is far short of the loss caused by self-demagnetization and may be essentially ignored.

Magnetic recording properties of tape

Tape has two fundamental magnetic properties, retentivity

(B_r) and coercivity (H_c). This is illustrated in Fig. 309 in Chapter 3. The drawing shows how the flux density (B) induced in the tape by the record head varies with the magnetizing force (H). Strictly speaking, the term B represents "surface induction," which refers to the density of the flux at right angles to the tape, this being the amount of flux that enters the playback head. Retentivity is the flux that remains in the tape after it is saturated and the magnetizing force is returned to zero. Thus (as shown in Fig. 309) after the tape's flux is brought to point c (saturation), when the magnetizing force H returns to zero, B does not also go to zero but remains, instead, at the level denoted by B_r .

To reduce the remaining flux to zero, a magnetizing force of opposite polarity to the original force is required. When a magnetizing force of opposite polarity attains the magnitude H_c , B is reduced to zero. H_c therefore is a measure of the force necessary to remove B_r .

The values of B_r and H_c vary with the nature of the magnetic coating found on each brand and kind of tape. Large values of retentivity are desirable for they increase the amount of flux recorded on the tape and therefore increase the signal output of the tape, particularly at low and mid-range frequencies. At high frequencies, however, greater values of B_r accomplish relatively little in the way of increasing signal output. Instead, the important factor at high frequencies tends to be coercivity—the ability of the tape to withstand record losses. Inasmuch as these losses are most pronounced in the treble range, coercivity plays a role in determining treble response.

Coercivity principally affects high-frequency response while retentivity helps determine low-frequency response. Therefore, the ratio of coercivity to retentivity, measured in the appropriate units, is an index of the relationship between high- and low-frequency response. The ability of tape recorders to achieve extended treble response at relatively low tape speeds is in substantial part due to the fact that manufacturers of tape have been able to increase the ratio of coercivity to retentivity, at the same time maintaining a high value of retentivity to insure high output.

The thickness of the magnetic coating is another factor in determining how well high-frequency response compares with low frequencies. The recorded flux on the tape penetrates the coating to a greater depth at low frequencies than at high ones. Therefore a thick coating tends to augment output at low frequencies.

Conversely, a thin coating tends to be detrimental to low frequencies, which means a relative improvement in high-frequency response.

There are variations in B_r among brands and kinds of tape and, as a result, for a given amount of signal input to the record head, the resulting output from the tape will vary. Within a reel of good-quality tape, the output variation in the low- and mid-frequency range is ordinarily $\pm 1/2$ db, which is insignificant for audio purposes. From one reel to another of the same kind and same manufacturer, the variation may be on the order of ± 1 db, which is still quite satisfactory. However, between brands there may be differences as great as 3 or 4 db. Consequently, if two brands of tape are spliced into the same reel, there may be a sudden and noticeable change in playback level!

Effect of recording level

Distortion on the tape is primarily determined by the strength of the magnetic field produced by the record head rather than by the amount of signal which gets recorded. Consequently, it is not feasible to compensate losses in the amount of signal recorded at high frequencies simply by increasing treble boost in the record amplifier. Before such treble losses can be completely compensated, the strength of the magnetic field applied to the tape is sufficient to cause excessive distortion.

The permissible record current and, therefore, the amount of magnetic flux which can be applied by the record head to the tape for a given level of distortion varies somewhat with recorded wavelength. Translating wavelength into frequency at a speed of 15 ips, $f = S/\lambda$, where f is the frequency in cycles per second, S is tape speed in ips, and λ is wavelength in inches per cycle.

The permissible record current tends to be constant over part of the low range and throughout the mid-frequencies. In the vicinity of 2,000 cycles, the permissible record current starts to increase until it is something like 4 or 5 db higher at 15,000 cycles. At a speed of 7.5 ips, this means that the rise begins at 1,000 cycles and is some 4 or 5 db higher at 7,500 cycles. At the low end, below 100 cycles or so, the permissible record current tends to drop a few db. The relationship between permissible record current and wavelength (which may be translated into frequency) varies somewhat among brands and kinds of tapes.

When all the magnetic domains on the tape are aligned in accordance with the magnetic flux produced by the record head,

there can be no further increase in the amount of signal recorded on the tape. This is the saturation point. However, distortion becomes appreciable at a signal level several db below that which produces saturation. It is important to distinguish between harmonic and intermodulation distortion, because IM distortion can become extremely severe at input signal levels which permit harmonic distortion to remain at a fairly acceptable point.

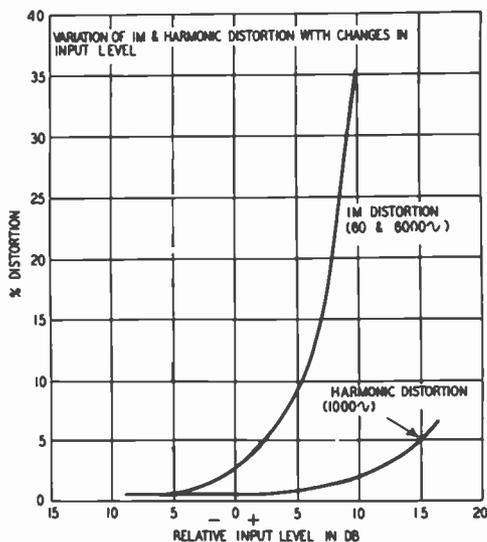


Fig. 401. Measurements of input level are based on the peak value of the test signals. The bias current is approximately optimum for the machine and tape used in making these measurements. 0-db input level corresponds approximately to a 0 reading on the tape recorder's VU meter. (Source: Audio, October, 1956.)

Fig. 401 indicates how harmonic and IM distortion vary with input signal and, consequently, with the magnetic flux recorded on the tape. It can be seen that IM distortion begins to rise considerably earlier than harmonic distortion and at a much faster rate. Thus, under the particular recording conditions present when the data in Fig. 401 were measured (tape used, bias setting, frequency equalization, etc.), harmonic distortion was only about 2%—not an unacceptable figure—while IM distortion was at a very pronounced level of 35%. Thus, when a recordist attempts to gain a few db of signal-to-noise ratio by increasing signal input to the record head, he runs the very serious risk of gaining it at the cost of a vast increase in IM distortion.

Tapes differ in their distortion characteristics. A test made by the authors, using five brands of tape, showed the following minimum amounts of IM distortion obtainable by varying the bias current until minimums were reached. A relatively high signal input was employed so that pronounced indications of IM distortion would be obtained.

Tape	Minimum IM Distortion (%)
A	7.6
B	9.0
C	11.0
D	10.0
E	3.5

While tape E seems preferable from the point of view of distortion characteristics, the final decision on which tape to use must include additional factors such as the tape's high-frequency response relative to the low and mid-ranges, whether the point at which high-frequency response begins to fall is very critical or fairly broad, and the tape's noise characteristics.

Tape noise and imperfections

In a tape recorder with heads well shielded to prevent hum pickup and with a well-designed and constructed amplifier, the principal component of noise will be that produced by the tape. Such noise takes two forms: tape hiss and "modulation noise."

When a tape is in the erased condition, its magnetic domains point in random directions. Although random orientation causes the magnetic fields of the domains to cancel, this cancellation, because it is random, is not complete. The small remaining amount of magnetization corresponds to an infinite number of frequencies more or less equally distributed through the sonic and ultrasonic spectrums. This is a form of noise known as tape hiss. Inasmuch as the upper part of the audio spectrum contains more frequencies per octave than does the lower part, more noise energy is present in the upper octaves than the lower ones. Consequently the noise takes on a high-frequency characteristic, although it contains low-frequency components as well.

Modulation noise arises partly from the fact that the tape's coating is not perfectly homogeneous from a magnetic point of view; that is, the magnetic particles are not evenly distributed throughout the resinous binder but tend to cluster somewhat. Also, it is partly due to the fact that the coating is not perfectly uniform in thickness, either because of defects in the coating or

irregularities in the base material. Both the magnetic and physical irregularities are translated into irregularities in recorded flux when the tape is subjected to a magnetic field in recording. These flux irregularities constitute noise.

The modulation noise, so to speak, is "developed" in the presence of a magnetic field, which may be either ac or dc. Fortunately, modulation noise is ordinarily greatest when the record signal is greatest and least when the signal is smallest, so this noise does not become more obtrusive during quiet passages.

Since both the dc and ac magnetic fields can produce modulation noise, it is important to avoid any dc components in addition to the audio signal. Such dc components can arise in various ways—from a magnetized head or an asymmetrical bias or erase waveform, which, in effect, contains a dc component.

A common tape imperfection, but one that manufacturers have been overcoming with increasing success, is that of "dropouts." This refers to small areas on the tape where the coating is too thin or contains an insufficient amount of magnetic material, resulting in sudden and brief decreases in output level.

Tape erasure

As seems reasonable to expect, the loudest signals recorded on the tape are the hardest to eradicate. Also, the mid-range and low frequencies, for a given recorded level, are the most difficult for the erase head to remove. Therefore, particularly if the tape has been recorded at an excessively high level, it is often necessary to employ a bulk eraser to obtain complete erasure. The bulk eraser—a relatively large ac electromagnet directly powered by the 117-volt 60-cycle line—can erase an entire reel in a few seconds.

Erasure is more difficult for recorded tapes that have been stored a long time or at warm temperatures. A "memory" effect has also been noted; that is, after a tape has been erased and stored, a slight amount of the erased signal reappears. This memory effect may be reduced by placing the tape in a warm place immediately after erasure and erasing again at a later date. However, for most audio recording purposes memory effect is not great enough to be noticeable.

Signal transfer

Signal transfer, sometimes referred to as print-through, post-echo or pre-echo, refers to the fact that the signal on one layer

of tape may appear on one or more adjoining layers above or below it on the reel. That is, the magnetic flux on the tape may be strong enough to magnetize adjoining sections of the tape through which this flux passes.

Since print-through is typically some 50 db below the original signal, signal transfer is unlikely to be noticeable at a moderate record level. But as the record level goes up, signal transfer increases at an even faster rate. Therefore, a high recording level (often found on commercial prerecorded tapes) or peaks on a normally recorded tape are likely to result in signal transfer. The pre-echo or post-echo that one sometimes hears on a phonograph record might be due to the original master tape, although the phenomenon is also common in the disc recording process.

Elevated temperatures can produce a substantial amount of signal transfer. So can the presence of magnetic fields although, of course, a sufficiently strong field will cause erasure. In fact, it is possible to copy, more or less successfully, one tape from another by running them together (magnetic coating against magnetic coating) through a properly adjusted magnetic field. Signal transfer increases slightly with storage, but not by an important amount.

bias current

BIAS current serves two fundamental purposes. It satisfactorily reduces the high distortion which otherwise would occur on the tape. It raises the recorded level sufficiently to produce an adequate signal-to-noise ratio in playback. However, at the same time that it performs these vital services, bias current can have undesirable effects with respect to high-frequency response and noise.

Various explanations have been advanced as to why bias increases output and reduces distortion. Some have employed mathematical approaches, some have tried to follow the complex magnetic behavior of the tape as it is subjected to the magnetic field resulting from the composite audio and bias currents. One reasoning is simply that in the presence of a bias field, which is very large compared with the audio field, the magnetic domains are in a state of agitation which decreases their resistance to magnetization.

No one theory has yet won unquestioned acceptance by all authorities. However, the effects of bias current on distortion and output are clear from an empirical point of view and shall therefore be approached in this manner. In the following discussion, the effects of bias current on output and distortion are shown for various frequencies. In all cases, a tape speed of 7.5 ips is assumed, but it should be clearly understood that the effects depend upon the wavelength recorded on the tape. However, the concept is more easily expressed in the familiar terms of frequency rather than in wavelength. Therefore, it is important to

remember, for example, that a given effect, described as taking place at 1,000 cycles when the speed is 7.5 ips, takes place at 2,000 cycles when the speed is 15 ips. An increase in tape speed removes a given effect to a proportionately higher frequency, which may be outside the audio spectrum. Thus an increase in tape speed affords a means of partially or completely escaping the detrimental effects of bias current upon frequency response, whereas a reduction in tape speed aggravates these effects.

Effect on tape output

Tape output is determined by the amount of flux recorded on the tape. Fig. 501 indicates how playback output at 1,000 cycles

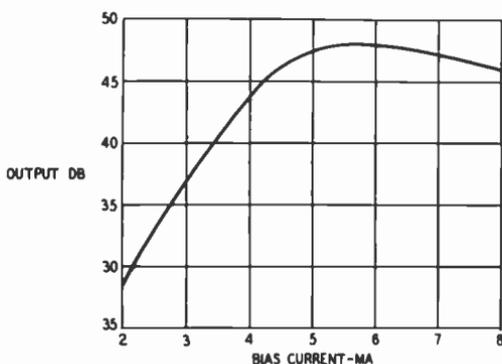


Fig. 501. Variation of output with bias current at 1,000 cycles. Data are for an Ampex model 300, 15-ips speed, audio current about 20 db below the level producing 1% harmonic distortion, 3M No. 111A tape. (Source: The 3M Co., Sound Talk Bulletin, No. 21.)

varies as the amount of signal current through the record head remains constant and bias current is increased. (The values of bias current shown are of no significance inasmuch as bias requirements vary substantially, depending upon construction of the head.) The output rises very substantially as bias goes up, reaches a maximum and then declines.

It might appear at first that bias should be set at the point corresponding to maximum output. However, there are other factors which also affect the proper bias setting. One is the amount of distortion at various levels of bias current and another the effect of a given amount of bias upon high-frequency response. Also, consideration has to be given to the sharp slope at the left

of Fig. 501, which indicates that in this area small changes in bias can produce considerable changes in output.

Effect on distortion

Fig. 502 illustrates what happens when a sine wave is recorded without the benefit of bias. The sine-wave input to the record head is represented on the vertical axis. The relationship between input (magnetic force) and output (recorded flux) for the tape in the absence of bias is shown by the "transfer characteristic"; this is analogous to the transfer characteristic for a radio tube, showing the relationship between input and output voltage. The waveform recorded on the tape, as indicated in playback, is represented on the horizontal axis, being the result of applying the

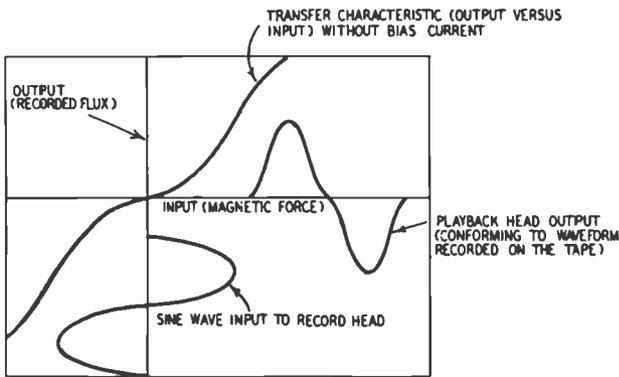


Fig. 502. *Reproduction of a sine wave without bias current.*

transfer characteristic to the input signal. (This is done by proceeding from a given point on the sine wave vertically to the transfer characteristic, then continuing horizontally to a point whose horizontal distance from the start of the output curve equals the vertical distance from the given point on the sine wave to the start of the sine wave. This procedure is repeated for enough points on the sine wave to define the output waveform.)

In Fig. 502 the output signal is considerably distorted. Since the distortion is symmetrical, it contains odd-harmonic multiples of the input frequency, which are in effect generated during recording. Thus, if a 1,000-cycle signal is recorded without bias, harmonic distortion will consist essentially of 3,000 cycles, 5,000 cycles, etc. The nonlinear transfer characteristic which produces harmonic distortion also causes IM distortion when two or more frequencies are recorded simultaneously.

Fig. 503 charts the relationship between bias current and distortion. Curves 1 and 2 refer to IM and curves 3 and 4 to harmonic distortion.

To produce fairly pronounced curves, a relatively high order of signal input was used. The curves were plotted, not for constant input level, but rather for constant playback level. Changes in bias current affect the amount of recorded flux and thereby the output level. But the important thing is how distortion varies with bias for a given amount of recorded flux. The amount of input signal required to produce this given flux is relatively of no concern for present purposes. Therefore the distortion-versus-bias relationships are plotted for a constant playback level.

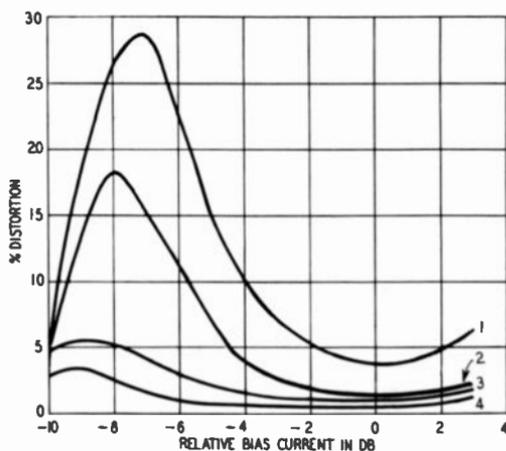


Fig. 503. Variation of IM and harmonic distortion with changes in bias current. Curve 1: IM distortion at playback level corresponding to +3 on VU meter. Curve 2: IM distortion at playback level corresponding to 0 on VU meter. Curve 3: Harmonic distortion at playback level corresponding to +3 on VU meter. Curve 4: Harmonic distortion at playback level corresponding to 0 on VU meter. (Source: Audio, October, 1956.)

Fig. 503 indicates: (1) Distortion in the main declines as bias increases, but there is a definite point of minimum distortion (more easily recognized in the IM curve) after which distortion rises again. (2) IM distortion is of greater magnitude than harmonic distortion. (3) IM distortion changes more rapidly than harmonic below and above the bias corresponding to minimum distortion. (4) The bias setting is the same for minimum IM and minimum harmonic distortion. (5) The higher the output level—that is, the recorded flux (curve 1 versus curve 2; curve 3 versus

curve 4)—the more critical is the bias setting for minimum distortion. (6) When bias is set for minimum distortion, an increase in output level produces less increase in distortion than at other bias settings.

An interesting phenomenon is displayed in Fig. 503. If bias is reduced far enough, distortion drops sharply after first reaching very substantial heights. However, it appears that at low output levels such reduced bias still produces more distortion than does normal bias. Moreover, to operate at subnormally low bias requires a vastly greater amount of driving power from the record amplifier to compensate for the lower tape output at such bias. Finally, at reduced bias levels the output level is relatively unstable because slight variations in bias produce large changes in output. (Fig. 501). Consequently, operation at exceptionally low bias has not been found practical for audio recording.

The relative values of bias for minimum distortion vary somewhat according to brand and kind of tape. For five tapes tested the bias settings that produced minimum distortion for a given output level are given in the following table. Tape A serves as a reference and its bias setting therefore is stated as 0 db.

Tape	Relative Bias Setting (db)
A	0.00
B	0.75
C	-0.50
D	0.00
E	-1.00

Among these five tapes, the bias setting for minimum distortion varied from -1.00 to $+0.75$ db, a 1.75 db range. While at first this may not appear to be very much of a deviation in terms of effect upon distortion, a variation of 1.75 db in bias setting can make a substantial difference in high-frequency response.

Effect on frequency response

Fig. 501 shows the effect of bias current on a frequency of 1,000 cycles. Fig. 504 is similar, but shows the effect on a number of frequencies. Although a relatively large amount of bias causes output to fall below maximum at all frequencies, it is important to note that the higher the frequency, the greater the decline in output. Thus the lower frequencies have fairly gentle downward slopes while the higher ones exhibit very sharp slopes. Maximum

output occurs at about the same bias value for all frequencies up to about 1,000 cycles but at higher frequencies the point of maximum output is reached much earlier. Consequently, if bias is set to maximize 1,000-cycle output (0.6 ma in Fig. 504), response at 15,000 cycles falls nearly 8 db below its maximum output. If bias is set at 0.8 ma (to reduce distortion further), then the response at 15,000 cycles is more than 15 db below maximum output.

An increase in bias current from 0.6 to 0.8 ma is only 2.5 db,

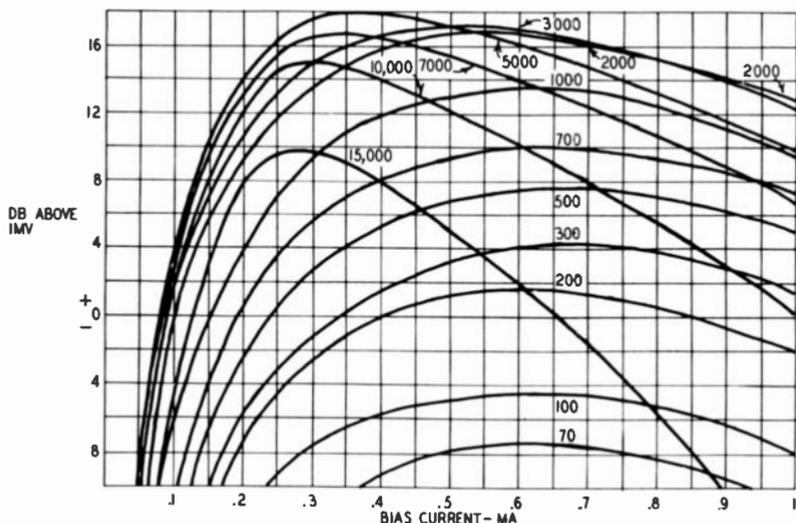


Fig. 504. Variation of output with bias current at various frequencies. Data are for a Brush BK-1090 head, operated at 7.5 ips. (Source: Otto Kornei, "Structure and Performance of Magnetic Transducer Heads," Journal of the Audio Engineering Society, July, 1953.)

yet Fig. 504 shows that it can produce a difference of about 8 db in output at 15,000 cycles. At 10,000 cycles, a bias shift from 0.6 to 0.8 ma reduces output nearly 5 db. And at lower frequencies such a bias shift has still smaller effect. Thus at 1,000 cycles there is an output difference of less than 1 db as bias is varied from 0.6 to 0.8 ma (Fig. 504). To summarize: extended high-frequency response—output in the region beyond 10,000 cycles—is quite sensitive to relatively small changes in bias. It can, therefore, be understood why a fair sacrifice in frequency response may be necessary to obtain a substantial reduction in distortion through an increase in bias.

A more direct way of showing the variation of frequency response with bias current is that of Fig. 505. The curves represent

the unequalized record-playback response of a tape recorder operating at 7.5 ips, employing a high-quality head (small gap and minor head losses). Three practical values of bias current for the head in question are used. As bias is increased, high-frequency output relative to the mid-range and low frequencies goes down. Consequently, at higher bias values a greater amount of high-frequency equalization is required to achieve flat treble response.

The reason for the adverse effect of bias current upon treble response lies in the fact that bias current, which may be 10 or more times greater than audio current, has an erasing effect similar to that produced by the erase head. Unfortunately, the high frequencies are most vulnerable to erasure because the magnetic flux which has just been recorded penetrates the tape less deeply than at low frequencies. The net result is that high frequencies are recorded at relatively lower magnitude.

Noise

Bias current not only plays a detrimental role with respect to treble response but is also a potent source of noise. To the extent that the bias waveform contains harmonic distortion, particularly second harmonic, which is the worst offender, noise is produced

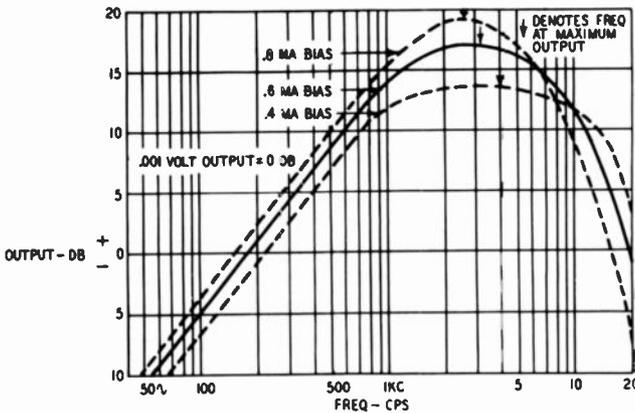


Fig. 505. Variation of unequalized record-playback characteristics with changes in bias current. Data are for a Dynamu D105 head, operated at 7.5 ips. This head has a physical gap of 0.00015 inch. (Courtesy, Dynamu Magnetronics Corporation.)

on the tape in the record process. Harmonic distortion in excess of 1% can have appreciably serious results.

Bias current that does not have a symmetrical waveform in effect contains a dc component; this current, via the record head, pro-

duces a magnetic field containing a dc component that develops modulation noise. Furthermore, the asymmetrical waveform will eventually magnetize the record head, which introduces a dc component that causes modulation noise in both record and playback. The record head can become magnetized in two ways: First, direct current may flow through the record head due to leakage through the coupling capacitors from the record-head driver and/or the bias oscillator. Second, even though the blocking capacitors are effective, the nonlinear characteristic of the heads at the relatively high value of bias current results in rectification, which causes the dc component to appear.

The asymmetrical waveform produced by the bias oscillator can similarly result in modulation noise via the erase head inasmuch as virtually all tape recorders use the same oscillator for bias and erase purposes.

(It is appropriate to mention, in connection with modulation noise produced by a magnetized head, that the playback head also tends to become magnetized due to the asymmetrical nature of audio waveforms recorded on the tape.)

Bias current can introduce spurious audio frequencies—noise—as the result of heterodyning between the bias frequency and upper harmonics of audio signal. For this reason it is recommended that the bias frequency be at least four or five times the highest audio frequency to be recorded. A factor of six or seven is preferable, although this raises various technical problems, including the fact that the erase head operates less efficiently as the frequency of the erase current rises.

Interdependence of performance characteristics

As earlier discussion has shown, frequency response varies with bias. Also, for a given recorded level, distortion varies with bias. Conversely, it is true that for a given amount of distortion, the recorded level varies with bias. The latter is equivalent to saying that the signal-to-noise ratio varies with bias, because noise in playback is usually the limiting factor, so that the larger the signal recorded on the tape, the greater the overall signal-to-noise ratio. In sum, frequency response, distortion, and signal-to-noise ratio are closely related to bias.

It may be seen, therefore, that these three vital measures of a tape recorder's performance are related to each other in large part through the effects of bias current. The interrelationship is of sufficient importance to merit extended treatment in this section.

Essentially, frequency response, distortion, and signal-to-noise ratio have a conflicting relationship, so that an improvement in a given respect can be attained only by a sacrifice in one or both of the other two. To make this clear, it is helpful to consider one characteristic at a time, show how it can be improved and indicate specifically how this improvement involves a sacrifice in the other characteristics.

Assume that it is desired to extend treble response. One way is to reduce bias current. High-frequency response suffers as bias is increased and, conversely, improves as bias is reduced. But a reduction in bias means greater distortion at high signal levels and possibly at all levels. To avoid increased distortion, one can reduce the record level, but then the signal level compared with noise and hum encountered in playback is smaller than before. In other words, the signal-to-noise ratio deteriorates. Quite possibly, an increase in frequency response may be obtained partly at the expense of distortion and partly at the expense of signal-to-noise ratio.

Another way to improve treble response is to increase the amount of treble boost in the record process; perhaps in the playback process, too. But more record treble boost may cause increased distortion in the upper range. This distortion can be avoided by lowering the record level. But, again, this entails a reduction in signal-to-noise ratio. If treble boost is added in playback, this means increased tape noise and, once again, a lower signal-to-noise ratio.

Assume that it is desired to reduce distortion. Usually this can be achieved through an increase in bias current. But greater bias means poorer high-frequency response. To prevent high-frequency loss, as already discussed, treble boost in recording may be increased but this invites higher distortion in the treble range unless the record level is reduced, which signifies a lower signal-to-noise ratio.

Assume, finally, that it is desired to increase the signal-to-noise ratio. This can be done by raising the record level, but then more distortion sets in. Increased bias may bring down this distortion, but, as before, at the cost of inferior treble response. Greater record treble boost can compensate the loss of high frequencies but, once more, higher distortion results, which calls for either more bias (thus continuing the vicious circle) or else for reducing the record level (which defeats the original objective).

It is apparent, therefore, that the designer and user of a tape

recorder must steer a compromise course among the conflicting requirements of extended treble response, low distortion and high signal-to-noise ratio. An optimum point has to be found, representing a suitable balance among the three factors.

Opinion as to the proper balance may well vary from manufacturer to manufacturer and from recordist to recordist. Thus one manufacturer may feel it imperative to maintain response no more than a few db down at 15,000 cycles at 7.5 ips and from this point of departure may seek the best balance between distortion and signal-to-noise ratio. Another may decide that the first consideration is to maintain a signal-to-noise ratio of at least 55 db and then find a balance between distortion and frequency response consistent with this ratio. Yet another may feel that low distortion is paramount, say 10% intermodulation distortion being the maximum permissible amount, and consequently from this point may try to achieve frequency response as wide as possible and a signal-to-noise ratio as high as possible. Finally, through advanced design and construction techniques, with cost a secondary consideration, a manufacturer may come up with a balance which, while not maximizing any one of the three basic performance requirements, nevertheless keeps each at a level consistent with high-fidelity standards.

The better tape amplifiers enable the recordist to vary bias and frequency equalization over a practical working range and, of course, record level is always under the recordist's control. Thus he can have a say in determining the balance among frequency response, distortion, and signal-to-noise ratio. Presuming the recordist has available a straightforward technique for achieving balance, he must first decide what standards of performance are compatible with high-fidelity reproduction. Personal judgment enters the picture here in a most important way.

For example, how important is it to have the frequency response clear out to 15,000 cycles? Is there a really substantial loss in *pleasurable* listening if response begins to drop rapidly after 10,000 cycles instead?

Again, what should be the maximum allowable distortion, that is, distortion during peak passages? A figure as low as 1 or 2% IM distortion, although usually cited in connection with high-fidelity equipment, is unrealistically low for most tape recording purposes. After all, peak passages come along just once in a while. Although the ear cannot endure substantial amounts of IM distortion, say 10%, for prolonged periods, very likely for

brief periods it can endure substantial amounts, perhaps as high as 20% or more.

With respect to signal-to-noise ratio, there is, relatively speaking, more certainty as to what meets a high-fidelity standard. Yet there is considerable room for divergence in views on the subject. Although ratios below 45 db produce quite noticeable noise, yet a person listening intently to the *music* can dismiss the unwanted background sound just as in a conversation-filled room a listener can concentrate on the one conversation that he wishes to hear and effectively filter out the others. So long as the background noise is of a constant nature—same level and same frequency characteristic—the listener can grow quite accustomed to it and dismiss it. Millions have played 78-rpm shellac records and found great musical pleasure despite the noise. To many such a listener, a rise in distortion would mean distress of much greater magnitude than the pleasure to be gained through less noise. On the other hand, there are persons less sensitive to distortion but very disturbed by the slightest noise.

With respect to all three performance characteristics, the nature of the recorded material can substantially affect what is considered acceptable. For example, certain types of music may impose relatively great demands with respect to keeping distortion low or frequency response broad. On the other hand, in recording the spoken word, a relatively large amount of distortion is tolerable, so that signal-to-noise ratio and, if desired, treble response as well can be improved.

All in all, there is no fixed rule as to what constitutes a proper balance among frequency response, distortion and signal-to-noise ratio. Trial and error and experience are perhaps the best guides.

In substantial part, the problem of achieving an optimum balance can be sidestepped by increasing tape speed. In other words, it is easier at a higher tape speed (15 ips rather than 7.5 ips) to find a balance satisfying the most people and most recording circumstances. This does not mean that such a balance cannot be achieved at 7.5 ips, which is the most popular speed for high-quality home recording. In fact, it is being achieved, although not so often as one would wish. However, at 15 ips it is easier to achieve a balance satisfying everyone.

Until quite recently, most professional recording was done at 30 ips to achieve top-quality results, but improvements in tape, heads, amplifiers and transports enable one today to achieve at 15 ips that which formerly required 30 ips. Similarly, the 7.5-ips

speed can now provide the quality once available at 15 ips, although a fair degree of effort is involved. It is quite possible, on the other hand, that the 7.5-ips speed will eventually fall into the luxury class because quality recording will be feasible at 3.75 ips or thereabouts.

More satisfactory results are obtainable at a higher speed, say 15 ips compared with 7.5 ips, because high-frequency losses (those due to bias erase, demagnetization and playback-head gap width) are largely a wavelength effect. The shorter the recorded wavelength on the tape, the greater the loss. A given frequency is represented by a wavelength twice as great at 15 ips as at 7.5. Hence the losses are distinctly less for a given frequency at 15 ips. This means that one can use greater values of bias current and smaller amounts of treble boost in recording at the higher speed. This results in less distortion and/or permits a higher record level (better signal-to-noise ratio). On the other hand, if it is not desired to reduce distortion or increase the signal-to-noise ratio, the treble range can be extended. Or one can do some of each.

There is still one more important consideration: Transports ordinarily perform better at high speed with respect to steadiness of motion. This is due to greater momentum of the rotating elements.

equalization requirements

EQUALIZATION rivals in importance any other single function of the tape amplifier. Not only is it vital as a means of achieving frequency response that is reasonably flat (consistent with tape speed), but it is also related to the distortion and signal-to-noise characteristics of the tape recorder.

The subject of equalization is divided into two chapters. The present one explains why equalization is needed and how it is achieved in terms of equalization curves and location of the necessary circuits. The next chapter is concerned with circuitry, examining the principal types of networks employed for bass or treble compensation and discussing their relative merits.

Recording without equalization

What happens if only the amplification, bias and erase requirements of the tape recorder are satisfied, but no equalization is provided? Fig. 601 contains the answer. The solid line shows the response characteristic at a speed of 7.5 ips; the dash line at 15 ips. Data are for a high-quality record-playback head operated at a practical bias level.

Fig. 601 obviously indicates the need for both bass and treble boost, the need for treble boost being greater at 7.5 ips. It shows that the amount of equalization required in the treble range varies inversely with tape speed and frequency.

Because of the 2-to-1 ratio between the speeds represented in Fig. 601, each point on the 15-ips curve bears an octave (2:1) relationship to a corresponding point on the 7.5-ips curve. Thus, the

point of maximum response is 6,000 cycles on the 15-ips curve and 3,000 cycles on the 7.5-ips curve. To illustrate further, at 15 ips the response at 10,000 cycles is about 8 db higher than at 1,000 cycles; at 7.5 ips, the response at 5,000 cycles is about 8 db higher than at 500 cycles. The 15-ips curve may be derived from the 7.5-ips one essentially as follows.¹ Each point on the 7.5-ips curve,

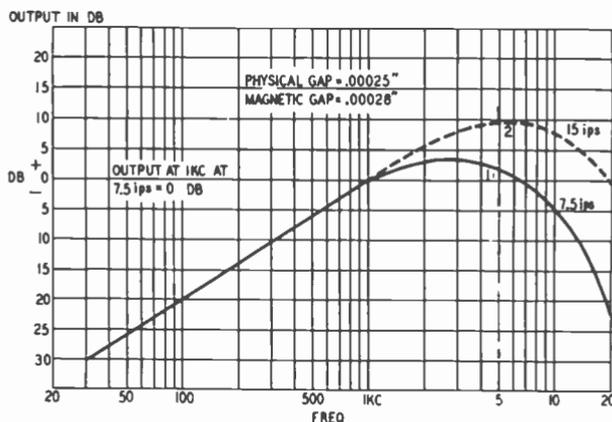


Fig. 601. Unequalized record-playback response of a high-quality head operating at 7.5 and 15 ips. Constant current used in recording. Bias in normal range.

representing a given wavelength, is shifted one octave to the right because at twice the speed a given recorded wavelength represents twice as high a frequency. These shifted points are then raised 6 db because doubling the frequency in playback means that the head produces twice as much output.

Although equalization is largely concerned with wavelength effects, it is less cumbersome and facilitates understanding to keep the discussion in terms of frequency. To do so means that it is necessary to assume a given tape speed. Therefore the discussion is in terms of effects observed at 7.5 ips, the speed most commonly used at present by home recordists interested in high fidelity. *However, unless specifically stated otherwise, the effects under discussion vary inversely with wavelength.*

Record and playback losses

The earlier analysis of head characteristics, tape characteristics and bias current has already indicated the various factors respon-

¹ To a relatively minor degree there are losses that vary purely with frequency, not with wavelength, and to this extent the octave relationship between curves 1 and 2 is not exact.

sible for the bass and treble losses shown in Fig. 601. The need remains, however, to assemble these various factors into one composite picture so that the reader may have an integrated view as to why equalization is required.

Record losses affect the treble range and are for the most part due to demagnetization and bias erase. Demagnetization refers to the fact that high frequencies recorded on the tape correspond to short bar magnets and the shorter the distance between the north and south poles of a magnet, the more these poles tend to cancel each other, thus reducing the magnetic flux on the tape. Bias erase refers to the fact that increases in bias current tend to reduce the amount of signal recorded on the tape, much more so at high frequencies than at low.

Demagnetization and bias erase are effects that vary with recorded wavelength. But there are other record treble losses that vary purely with frequency, regardless of the speed at which the tape recorder is operated. These so-called "head losses" are of three kinds: (1) those due to capacitance between turns of the head winding; (2) those due to eddy currents circulating in the core of the head; (3) those due to hysteresis of the core. Losses caused by eddy currents and hysteresis are referred to as "iron losses." When a high-quality head is used, these losses are kept to a minimum within the audio range, sometimes in the order of only 1 db.

In playback, both bass and treble losses are significant. The principal reason for bass loss is the "constant-velocity" characteristic of the playback head. As previously explained the output of the head tends to be proportional to the rate at which the magnetic flux of the tape changes polarity. The lower the frequency, the slower the rate of change and hence the less the output. A minor reason for bass loss at the very low end (largely below 50 cycles) is the wrap effect; that is, the material of the head may adversely affect magnetic coupling between the tape and the playback head gap when the magnetic flux extends an appreciable distance from the tape. This is the case at very low frequencies.

Treble losses in playback are essentially those due to the gap. The narrower the gap, the better its ability to reproduce high frequencies. Shortly above the frequency where the recorded wavelength becomes so small that it is only twice the width of the gap, the response drops very abruptly. All heads presently used in audio tape recorders have some losses due to gap width, but the top-quality heads have gaps narrow enough to insure that the

drop in response at 15,000 cycles (at 7.5 ips) is no more than about 5 db.

The other treble losses that occur in playback are due to winding capacitance and the so-called iron losses. Winding capacitance loss is more likely to occur in a head designed expressly for playback than in one designed also for recording. The reason is that such a playback head has a large winding to maximize output whereas in the record/playback head the winding must be limited so that the bias current is not excessively attenuated.

The principal factors responsible for the losses that occur in the tape recording and reproduction processes are portrayed in Fig. 602. The data are based on a high-quality record-playback head, bias current within the normal range and the tape operating at 7.5 ips. Starting with the theoretical 6-db-per-octave rising characteristic throughout the audio range a loss-free playback head would produce if the tape contained the same magnetic flux at all frequencies, high-frequency response is successively reduced by record loss due to bias erase and demagnetization, by playback loss due to gap width, and by other record and playback head losses (winding capacitance and iron losses). The final result is the unequalized record-playback response curve of Fig. 601.

The only loss not specifically represented in Fig. 602 is the so-called wrap loss at the low end in playback. This can differ substantially from one head to another and in a well-designed head can be brought below the audio range. Moreover, the contour effect may offset wrap loss, possibly to an extent where there is a slight rise in response at the low end relative to the 6-db-per-octave rising playback characteristic.

It is assumed that the tape amplifier does not contribute to bass and treble losses, but is essentially flat—apart from the equalization circuits—over the audio range.

Location of equalization circuits

It is apparent from Fig. 602 that substantial amounts of bass and treble equalization are required in the tape-recorder amplifier to achieve a reasonably flat response. This compensation may be provided either in record or in playback or partly in each. The course followed can make a substantial difference in signal-to-noise ratio and distortion. The ideal is to put as much signal as feasible on the tape at all frequencies. Accordingly, the location of equalization circuits should be governed by the following general principles, which bring out a vital distinction between bass and treble boost.

Bass-boost location

Fig. 601 shows that over 30 db of bass emphasis is required. Taking into consideration that there is a dropoff in audio energy at the low-frequency end, some bass equalization during record is feasible, but record bass boost on the order of 30 db would result in tremendous low-frequency distortion on the tape. True, the record level could be reduced to avoid this distortion, but

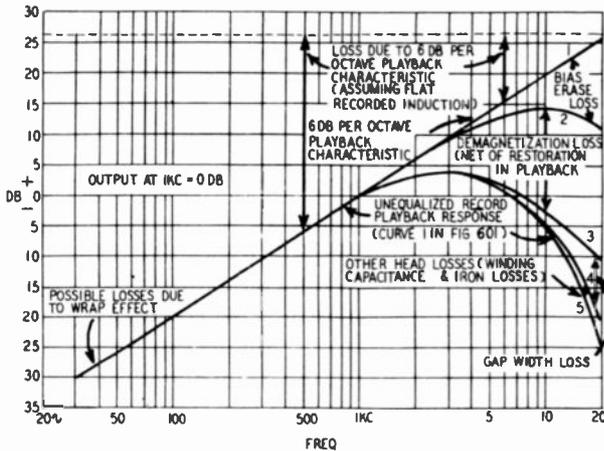


Fig. 602. Principal factors responsible for 7.5-ips record-playback response shown in Fig. 601.

then the signal-to-noise ratio would suffer by the same amount. Consequently, bass equalization must take place primarily in the playback amplifier for high-quality results.

Playback bass boost limitations

On the other hand, it is not desirable to continue playback bass boost to an inordinately low frequency, partly because of low-frequency noise and hum and partly because it is expensive in terms of amplification stages to carry equalization to an extreme point. Therefore, playback bass boost should level out around 50 cycles instead of continuing at the rate of 6 db per octave to a much lower frequency. If it is desired to maintain record-playback response reasonably flat to 30 cycles or lower, it becomes necessary to incorporate bass boost for the range below 50 cycles in the record amplifier. A few db of bass boost in record will do no harm with respect to distortion.

Treble-boost location

To the extent that treble boost takes place in playback, it not only raises the level of high-frequency audio signals but also emphasizes tape hiss and noise in the early stages of the playback amplifier. Therefore, playback treble boost results in deterioration of the signal-to-noise ratio. For this reason and because the distribution of energy in the audio spectrum makes it feasible, treble boost should take place primarily in record. Typical audio sources exhibit a considerable dropoff in energy above the middle of the audio range. To the extent that treble boost is offset by declining audio energy, more or less the same amount of magnetic flux is applied to the tape over the upper range, thus avoiding an increase in distortion. Moreover, as the frequency increases, the strength of the magnetic field that can be applied to the tape for a given level of distortion goes up somewhat.

However, there is a limit to the magnetic flux which can be applied to the tape and thus there is a limit to the treble boost that can satisfactorily be employed in recording. Accordingly, depending upon tape speed, it may be necessary to settle for a frequency response which does not span the entire treble range. Otherwise, distortion may rise and/or signal-to-noise ratio may fall in order to preserve full treble response.

A limited amount of treble boost may be used in playback. The extent of this boost should correspond at the most to treble losses due to gap width, winding capacitance and iron losses of the playback head as well as to cable and input tube capacitances. However, this does not mean that satisfactory performance can be had by using a head with relatively large losses and compensating for such losses by a large amount of playback treble boost. This, of course, would result in a poor signal-to-noise ratio. For high-quality results, treble boost in playback should be limited so that it does not exceed roughly 6 db at 15,000 cycles.

A valid reason for permitting some treble boost in playback is that head losses vary from one head to another. If a tape recorded on one machine is to be played back on another, ordinarily one cannot anticipate the head losses of the playback unit. Therefore, it is logical that treble losses due to the playback head should be compensated in the playback amplifier rather than the record amplifier.

While this approach to the location of bass and treble-boost circuits will insure optimum results, it is not followed by all recorders. As a rule, today's professional and semiprofessional

machines adhere to these principles by virtue of the fact that they basically conform to the NARTB standard which embodies them. But many (if not most) home tape recorders deviate from the NARTB standard because of the cost factor. They use the same, or almost the same, equalization in record and playback; that is, half the required equalization is provided in record and the other half in playback, for bass and treble alike. Although the results thus obtained can be satisfactory, they are not as good as those obtained by confining bass boost primarily to playback and treble boost primarily to record. The greater amount of bass boost in record threatens distortion, unless the record level is reduced, thereby decreasing the signal-to-noise ratio. And the greater amount of treble boost in playback augments tape hiss and amplifier noise, further reducing the signal-to-noise ratio.

Basic equalization pattern

Before discussing the problem of equalization in terms of specific curves and frequencies, it is desirable to consider the subject in basic, generalized terms. Such an approach will help make clear a vital point: the turnover frequency (3-db rise) at which bass boost begins in playback serves to determine the amount of treble boost needed in record.

The lower the playback turnover frequency, the less the record treble boost required. In other words, equalization may be effected either by using a large amount of playback bass boost together with a large amount of record treble boost, or by using a small amount of each. However, reduced equalization, while mitigating problems of low-frequency noise and of distortion due to excessive record treble boost, at the same time results in an inferior signal-to-noise ratio. This is so because less signal is recorded on the tape.

Figure 603 represents the basic pattern of equalization in a high-quality recorder. Line A-B covers the range over which flat response is feasible (although in practice the response is allowed to drop slightly at each end of the range). f_1 is the lowest frequency in this range and f_3 the highest. f_2 is the turnover frequency, the point at which the various curves shown have either risen or declined 3 db from a previously flat course.

Line C-D is the response of an ideal playback head, one without losses or aberrations of any sort, rising 6 db per octave throughout the range. This response assumes that the amount of magnetic flux recorded on the tape is the same at all frequencies; in other words, the record amplifier has compensated all record

losses by means of treble boost. The slope of line C-D is illustrated in Fig. 603.

Line C-D may be viewed as either bass droop or treble rise, depending upon the location of turnover frequency f_2 . The portion above f_2 may be viewed as a rise in response. It may be seen, therefore, that the rising characteristic of the playback head in effect supplies treble boost above f_2 .

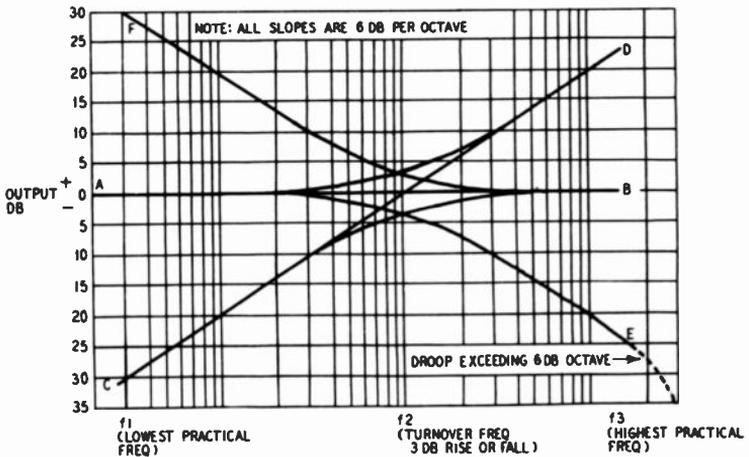


Fig. 603. Basic pattern of equalization in a tape recorder. AB: range of flat response; CD: response of an ideal head to flat recorded flux; AE: actual recorded flux; CB: response of an ideal head to actual recorded flux; FB: bass boost required to flatten curve CB.

This treble boost due to the playback head is needed to compensate for the fact that magnetic flux recorded on the tape is not flat, as previously assumed, but drops off at the high end. Curve A-E is the actual frequency characteristic recorded on the tape. Because of the large magnitude of record losses, it is impractical to record flat at the lower tape speeds (15 ips and less). This would necessitate tremendous treble boost, leading to excessive distortion or else a vast reduction in recorded signal level and hence in signal-to-noise ratio. Consequently, the recorded flux is permitted to decline at the treble end. f_2 defines the frequency at which recorded flux is 3 db down. Record treble boost has to be such that curve A-E declines at a rate approaching 6 db per octave.

The rising response characteristic of the playback head above f_2 compensates for the declining portion of A-E above f_2 . The combined result of curves C-D and A-E is curve C-B, namely playback response before bass boost. This should essentially be

supplied in playback (although the less expensive recorders often supply a substantial portion in record). To achieve flat response, curve F-B compensates curve C-B. F-B in a high-quality recorder is essentially *playback* bass boost.

Since playback equalization (F-B) is determined by playback response before such equalization (C-B) and since the latter in turn is determined by recorded flux (A-E), it is apparent that playback equalization and recorded flux are directly related to each other. Given one, the other is defined (assuming flat overall

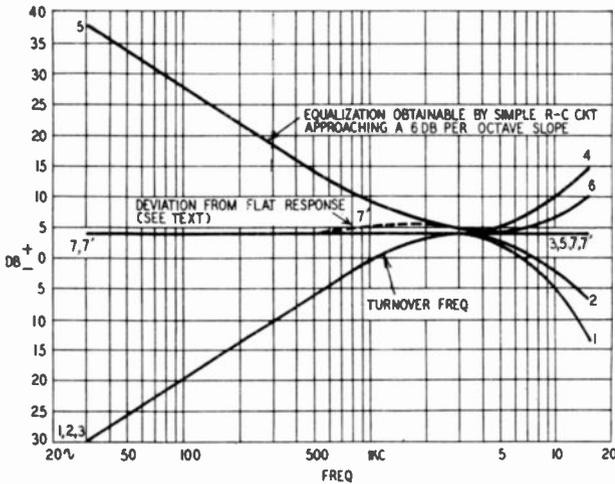


Fig. 604. Equalization of 7.5-ips record-playback response in Fig. 601. Minimum equalization. A slight deviation from flat response occurs between 600 and 5,000 cps because curve 5 conforms to a 6-db-per-octave characteristic and therefore does not exactly complement curve 3. 1: unequalized record-playback response (Fig. 601); 2: unequalized record-playback response without playback-head losses; 3: desired playback response for flat treble response; 4: required record boost for flat response (3-2); 5: required playback boost for approximately flat bass response (7'-3); 6: required playback boost for flat treble response (2-1); 7: equalized (flat) response.

response). Thus the equalization of a tape recording system can be stated either in terms of the magnetic flux recorded on the tape or in terms of the bass-boost characteristic of the playback amplifier. It is much easier and more practical to supply the definition in terms of playback bass boost.

If the turnover frequency f_2 were reduced (shifted to the left), less bass boost (F-B) would be required. At the same time, this would shift the recorded flux (A-E) to the left. In other words, recorded flux would begin to decline at a lower frequency. There-

fore less record treble boost would be needed to provide the stipulated flux characteristic. The greater drop in recorded flux at any given treble frequency would be compensated by the fact that the rising characteristic of the playback head (above f_2) would begin at a lower frequency, resulting in greater treble boost. Thus one can realize the important fact that smaller amounts of bass boost in playback go hand in hand with smaller amounts of treble boost in record, and vice versa.

Specific equalization patterns

In the following discussion, all references to Fig. 601 pertain to the unequalized record-playback response at 7.5 ips.

Fig. 604 shows theoretically how this unequalized response, redrawn as curve 1, can be equalized with a minimum of treble and bass boost. As a matter of fact, an approach of this sort is taken by many moderate-price recorders inasmuch as the less the equalization, the less the problem of providing enough gain to overcome the insertion losses due to equalization. Also, reduced playback bass boost minimizes hum problems.

Fig. 604 is idealized in the sense that it shows equalization such as to produce a response flat from 30 to 15,000 cycles. In practice, even the best recorders do not attempt to maintain flat response over this range at 7.5 ips. Instead, they permit a few db droop at both ends. This reduces problems of low-frequency noise, of providing sufficient gain, of possible distortion due to excessive treble boost, of decreasing the signal-to-noise ratio due to high-frequency boost in playback, etc.—all at a cost of so slight a deviation from flat response that it is nearly or completely unnoticeable. For ease of presentation, however, it is easiest to show full equalization from 30 to 15,000 cycles, especially since recorders vary substantially as to the amount of droop at each end. "Flat" equalization will also be shown in the remaining figures in this chapter, unless specifically noted otherwise.

Curve 3 in Fig. 604, corresponding to C-B in Fig. 603, represents flat treble response in playback, *with bass still remaining to be compensated*. The difference between curves 1 and 3 is due to two factors: record treble losses and playback-head treble losses. As previously stated, record treble losses should be compensated in the record amplifier and playback-head treble losses should be compensated in playback. Accordingly, record losses are compensated by curve 4, which equals the difference between curves 2 and 3. Curve 2 is the unequalized record-playback response with-

out playback-head losses. Playback-head losses, which equal the difference between curves 1 and 2, are compensated by curve 6.

It remains to compensate curve 3 by bass boost to achieve overall flat response, depicted by curve 7. Thus the amount of playback bass boost needed is the difference between curves 7 and 3. It is general practice to use a simple R-C circuit, approaching a 6-db-per-octave slope, to achieve bass boost for playback purposes. Curve 5, corresponding to F-B in Fig. 603, is of this type, and its turnover point (3-db rise) is selected so that curve 5 complements curve 3 over as much of the required range as possible. Consequently, curve 7 *actually* is not flat, as shown by its dashed portion 7'. However, the deviation from flat response is relatively minor being 1.5 db at most.

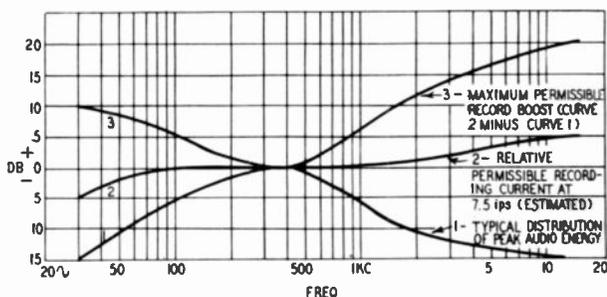


Fig. 605. Approximation of maximum permissible treble and bass boost in recording.

Although the scheme of equalization in Fig. 604 is quite feasible and demands only 10.5-db record treble boost, it fails in a very important respect. It does not produce as much signal-to-noise ratio as practicable. To maximize this ratio, it is necessary to put on the tape as much signal as possible without incurring excessive distortion. This Fig. 604 does not do.

Music, speech and other audio material most commonly recorded on tape have substantially less energy at the high frequencies than in mid-range. Energy also drops off at the low end. The approximate nature of the distribution of audio energy is shown in curve 1 of Fig. 605. It must be stressed that this curve is not definitive but represents only a smoothed version of a typical situation, in this particular case an orchestra. On the other hand, curve 1 is representative enough to be useful for the present discussion. Curve 1 shows the relative distribution not of average, but of peak levels. It is these peak levels that are of concern with respect to the tape's ability to handle signals without excessive distortion.

To the extent that high frequencies have a relatively small peak amplitude, it is possible to boost them in the record amplifier without overloading the tape. Furthermore, for a given amount of distortion, the tape can be exposed to somewhat larger magnetic fields at high frequencies, as indicated roughly in curve 2 of Fig. 605. Therefore, the amount of record treble boost which can be safely employed is represented by curve 3, obtained by taking the difference between curves 2 and 1 (or by adding the absolute differences between each curve and the 0-db line).

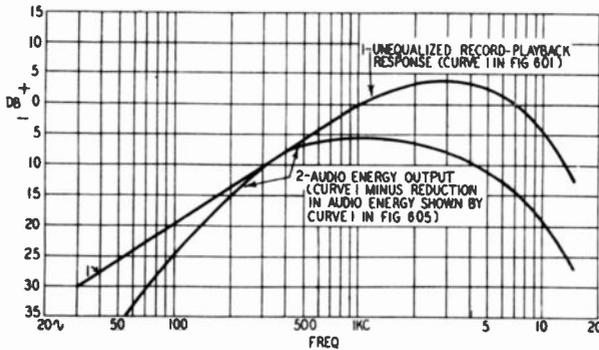


Fig. 606. Approximate audio energy output of record-playback head in Fig. 601.

The unequalized record-playback response in Fig. 601 (curve 1) is predicated on constant current in recording; in other words, it assumes the same level of signal input at all frequencies. Realistically, however, when dealing with a typical audio source, the unequalized audio output is similar to that depicted by curve 2 in Fig. 606. This equals curve 1 in Fig. 601 less the reduction in audio energy at various frequencies shown by curve 1 in Fig. 605. The difference in Fig. 606 between curves 1 and 2 in the treble region indicates to a substantial extent how much the signal-to-noise ratio can be improved by treble boost in record.

Looking at Fig. 604, the maximum of 10.5-db record treble boost (at 15,000 cycles) is considerably short of the maximum of 20-db boost which can safely be used according to Fig. 605.

Fig. 607 shows the equalization which might be used to maximize the signal-to-noise ratio, assuming a maximum permissible record boost of 20 db at 15,000 cycles per curve 3 of Fig. 605. Curves 1 and 2 are the same as in Fig. 604, showing unequalized record-playback response with and without playback-head losses. Curve 3, representing flat *treble* response in playback, is chosen on the following two bases: (1) to achieve overall flat response it

can be matched by a playback bass-boost curve having a 6-db-per-octave slope produced by an R-C circuit; (2) the amount of record boost required for flat treble response will reach a maximum of 20 db at 15,000 cycles. Put differently, at 15,000 cycles the difference between curves 3 and 2 is 20 db.

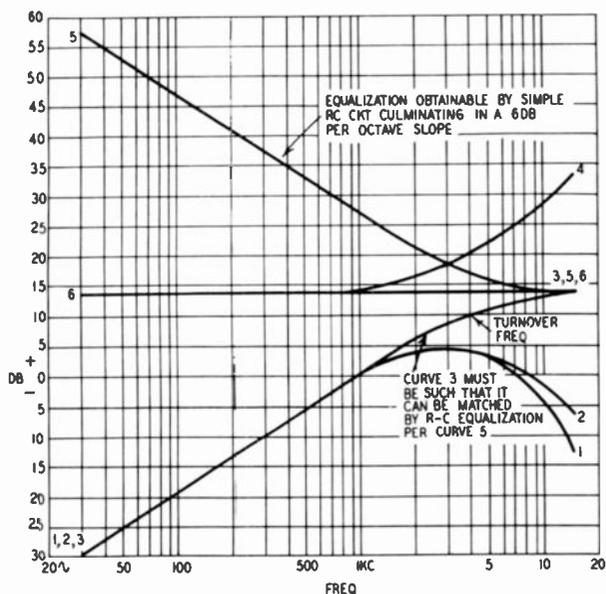


Fig. 607. Equalization of 7.5-ips record-playback response in Fig. 601. Maximum signal-to-noise ratio. 1: unequalized record-playback response; 2: unequalized record-playback response without playback-head losses; 3: desired playback response for flat treble response; 4: required record boost for flat treble response (3-2); 5: required playback boost for flat bass response (6-3); 6: equalized (flat) response.

Comparing Figs. 607 and 604, curve 3, which in each case is the desired playback response for a flat treble characteristic, has considerably more amplitude in Fig. 607. This difference in amplitude corresponds to the difference between the treble-boost curves (curve 4) in the two figures. In other words, a tape recorded according to Fig. 607 has considerably more treble signal on it and therefore a higher signal-to-noise ratio in playback.

To achieve a flat response out to 15,000 cycles, it would be necessary to use playback treble boost equal to the difference between curves 2 and 1, representing playback-head losses. This boost is not shown in Fig. 607, being the same as curve 6 in Fig. 604.

Given a playback response such as that of curve 3, obtained by proper treble boost in record and playback, it remains only to supply the playback bass boost of curve 5 to achieve overall flat response. Curve 5 equals the difference between curve 6, which denotes flat response, and curve 3.

NARTB standard equalization

At this writing, the only official tape equalization standard is that established in June, 1953, by the National Association of Radio & Television Broadcasters for 15 ips. However, owing to improvements in tapes, heads and tape amplifiers, this standard has also been considered suitable for 7.5 ips recording. Therefore, NARTB equalization or a close approximation to it is, in reality, a standard for 7.5-ips, followed principally by manufacturers of quality recorders and manufacturers of prerecorded tape. A leader in utilizing NARTB equalization (a close approximation) at 7.5 ips has been Ampex Corp., whose tape recorders figure most prominently in making original and duplicate commercial tapes. Accordingly, the terms "NARTB equalization" and "Ampex equalization" are nearly synonymous at 7.5 ips. In addition, there is an Ampex characteristic for 3.75 ips, widely followed in the commercial field.

NARTB equalization is essentially stated in terms of a specific bass-boost characteristic in playback. Losses due to the playback head require compensation by the playback amplifier. The record amplifier is required to have equalization that will then produce playback response meeting NARTB standards. This standard provides for ± 1 -db deviation between 100 and 7,500 cycles. Below and above these frequencies the response may gradually deviate more widely. The upper limit remains at 1 db; the lower deviation limit declines at the rate of 3 db per octave so that it is -2 db at 80 cycles, -3 db at about 60 cycles and -4 db at 50 cycles. The upper deviation limit also declines at 3 db per octave so that it is -2 db at 9,500 cycles, -3 db at 12,000 cycles and -4 db at 15,000 cycles. In brief, response may be 4 db down at 50 and 15,000 cycles.

Curve 1 in Fig. 608 represents the NARTB playback bass-boost characteristic. Formed by R-C circuits, it consists of a 6-db-per-octave slope which begins at 3,180 cycles (3-db rise) and levels off at 50 cycles (3 db below maximum boost). Inasmuch as the playback boost levels off at the low end, a flat response requires a corresponding bass boost in record, as shown by curve 2'.

Omission of this relatively small amount of record boost might not appear to violate the NARTB standard in view of the fact that response is permitted to be down 4 db at 50 cycles, whereas the boost of curve 2' is only 3 db at 50 cycles. However, omission of record bass boost presumes that the playback head can maintain flat response down to 50 cycles. Since this may not be true, it is proper to consider curve 2' as part of the NARTB recording standard.

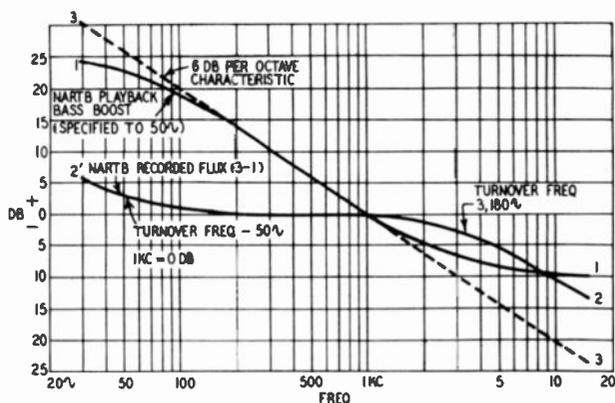


Fig. 608. NARTB equalization.

Here the reader may well ask: Should not standard equalization refer to a specific record characteristic? The answer is that the NARTB standard, although expressed in terms of playback bass boost, does inferentially denote a specific amount of relative recorded flux at various frequencies, as shown by curve 2'-2. The playback curve and the recorded flux bear a fixed relationship to each other, so that one defines the other. It is more convenient, however, to express the standard in terms of playback bass boost, which can easily be measured by relatively simple means, principally with the aid of an audio oscillator and a vacuum-tube voltmeter. Measuring the recorded flux, on the other hand is an involved process requiring expensive laboratory equipment.

NARTB playback bass compensation, in essence, does two things: (1) it compensates for the playback head's 6-db-per-octave rising characteristic (disregarding head losses, which are compensated by a separate treble-boost curve); (2) it compensates for the variation of recorded flux with frequency, according to the NARTB standard. Consequently, by removing the 6-db-per-octave slope from the NARTB bass-boost curve, NARTB recorded flux is revealed. This is done in Fig. 608. Curve 3 is a 6-db-per-octave

slope. Subtracting curve 1 from curve 3 produces curve 2'-2, namely NARTB standard recorded flux.

As can be seen in Fig. 608, the NARTB record characteristic has a turnover frequency (3 db down) of 3,180 cycles. In other words, recorded flux does not drop significantly until 3,180 cycles. The reasons for choice of the 3,180-cycle turnover frequency at a speed of 15 ips are concerned with the relative distribution of energy over the audio spectrum, the permissible record current which can be employed at various frequencies and the unequalized record-playback response of a typical head at 15 ips.² Although the standard was adopted in June, 1953, work leading to its formulation began several years earlier when tapes and heads had not reached their present state of development so far as high-frequency response is concerned. Consequently, a standard which at the time of formulation was considered suitable only at 15 ips (or higher) was subsequently found also suitable for 7.5 ips. In other words, the recorded flux shown in Fig. 608 can be attained at 7.5 ips with record treble boost that is admittedly high but within practical bounds, and playback heads can come within a few db of flat response at 15,000 cycles.

In this connection, Fig. 607 shows that a turnover frequency as high as 4,500 cycles is possible at 7.5 ips; that is, even a greater amount of flux could be put on the tape at 7.5 ips than is required by the NARTB characteristic. However, it must be remembered that the turnover frequency shown in Fig. 607 is based on the original unequalized record-playback response curve before playback-head losses (curve 2 in Fig. 607). In turn, curve 2 is determined by the amount of bias current used. Although bias current is in the normal range, as originally indicated in Fig. 601, it is still below the amount which would produce minimum distortion. Higher bias would cause curve 2 to drop more sharply at the high end, thus reducing the feasible amount of flux that could be put on the tape. Since low distortion is as important an objective of quality recording as high signal-to-noise ratio, it must be realized that a turnover frequency lower than 4,500 cycles would probably permit better overall results. Thus, a turnover frequency of 3,180 cycles is consistent with higher bias and somewhat less signal-to-noise ratio.

In fact, it is argued that 3,180 cycles is still too high a turnover

² W. E. Stewart, "Why the NARTB Curve for Magnetic Tape," *Radio & Television News*, June, 1955. Mr. Stewart was a member of the NARTB Subcommittee on Magnetic Recording Standards.

frequency for 7.5 ips and that a lower turnover frequency would require less record treble boost, resulting in less distortion, or that for the same amount of treble boost, higher bias current could be employed, serving to reduce distortion. On the other hand, the proof of the pudding is in the eating, and today excellent results are being obtained by high-quality tape recorders operating at 7.5 ips and using NARTB equalization (or very close to it).

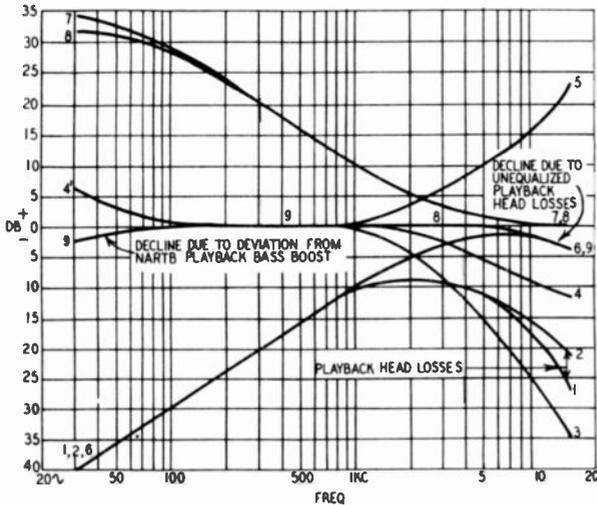


Fig. 609. Equalization of a high-quality tape recorder operating at 7.5 ips. 1: unequalized record-playback response; 2: unequalized record-playback response without playback head losses; 3: treble record losses; 4'-4: required recorded flux (approximately NARTB); 4': required record bass boost; 5: required record treble boost (4-3); 6: equalized treble response (1 and 5); 7: required NARTB playback bass boost; 8: Ampex playback bass boost; 9: equalized bass and treble response (6 + 4' + 8).

Fig. 609 shows the complete pattern of equalization in a high-quality tape recorder using Ampex 7.5-ips equalization, which essentially conforms to the NARTB standard. Curves 1 and 2 are similar to those in Figs. 604 and 607, being the unequalized record-playback response with and without playback-head losses. Such losses (difference between curves 1 and 2) are small enough (about 5 or 6 db at 15,000 cycles) so that the NARTB frequency standard (2 db down at 10,000 cycles and 4 db down at 15,000 cycles) can be nearly met without compensating for them by playback treble boost. Instead, 1 or 2 db additional treble boost are

used in record so that recorded flux (curve 4'-4) represents a slight departure from the NARTB standard.

Curve 3 shows the treble losses encountered in recording, while curve 4 is the Ampex recorded flux characteristic at the treble end. The difference between curves 3 and 4 dictates the required treble boost, represented by curve 5. Curve 6 shows the playback response when record treble boost is supplied but record and playback bass boost are omitted. Curve 4' shows NARTB record bass boost. Curve 7 shows the necessary playback bass boost to achieve perfectly flat bass response. However, the amount actually supplied is slightly less, as shown by curve 8. The resulting overall response is the sum of curves 6, 4' and 8, which results in about 1.5-db loss at 40 cycles and 2.5-db loss at 30 cycles, which is well within the NARTB frequency response requirements.

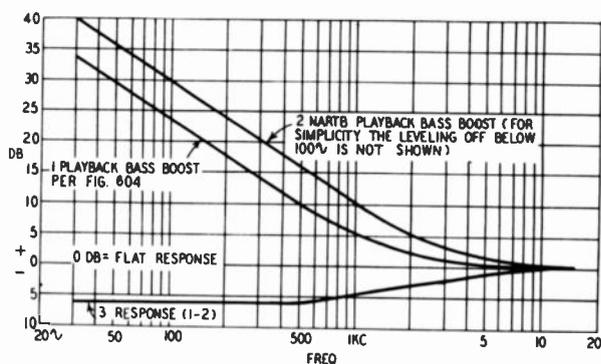


Fig. 610. Response of a tape recorder with playback bass boost per Fig. 604 to a recorded tape requiring NARTB playback bass boost.

Although NARTB equalization is feasible at 7.5 ips, it is not yet in universal use at this speed. Many or most moderate-price recorders use equalization such as in Fig. 604, where the turnover frequency is in the range of 1,000 to 1,500 cycles. What happens if tape recorded according to the NARTB standard is played back on such a machine, as often happens today when commercially prerecorded tape is used? The result is shown in Fig. 610. Curve 1 shows the bass boost that might be supplied by a moderate-price unit (curve 5 in Fig. 604), while the required NARTB bass boost is shown in curve 2. The difference between actual and required bass boost results in the response characteristic of curve 3. This response may be viewed as being either deficient in bass or having exaggerated treble. To an extent, a cut in treble by means of a tone control would flatten curve 3. However, it is un-

likely that the characteristics of the tone control would exactly match the slow, long treble rise of curve 3. Consequently, there would still be some unevenness of response.

The 3.75-ips speed is very popular for home use because it doubles the playing time of a reel of tape and at the same time affords a frequency response to approximately 7,500 cycles, quite acceptable in many circumstances. As a result, some commercial prerecorded tapes are being offered at 3.75 ips. Although there is no unofficial or official NARTB standard at this speed, Ampex equalization is generally used by manufacturers of prerecorded tape as well as by some manufacturers of tape recorders. Ampex 3.75-ips equalization basically parallels the NARTB standard, except that the turnover frequency is reduced two octaves, although there is only a 1-to-2 ratio between the 3.75- and 7.5-ips speeds.³ Therefore the 3.75-ips turnover frequency is 795 cycles.

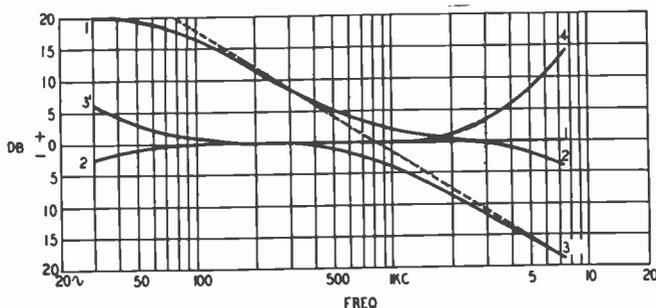


Fig. 611. Ampex equalization of a tape recorder operating at 3.75 ips. 1: Ampex bass boost; 2-2: equalized response; 3-3: required record characteristic; 4: required treble boost to compensate treble record losses.

Ampex equalization of a tape recorder operating at 3.75 ips is depicted in Fig. 611. Curve 2-2 represents the equalized overall response, which is 2.5 db down at 30 cycles as in the case of 7.5 ips, but 4 db down at 7,500 cycles. Curve 1 is Ampex playback bass boost and curve 3-3 the corresponding recorded flux characteristic. The required record treble boost is shown by curve 4.

Although the record losses compensated by curve 4 are not shown, these can be derived by subtracting curve 4 from curve 3. It will be remembered from Fig. 609 that record treble boost rep-

³ This tends to support those who feel that 3,180 cycles is too high a turnover frequency at 7.5 ips. They claim that 15-ips NARTB equalization should be scaled down one octave whenever tape speed is cut in half. Thus, it is held, 7.5-ips equalization should have a turnover frequency at 1,590 cycles and 3.75-ips equalization at 795 cycles.

resents the difference between the required recorded flux and record losses. Finally, owing to the limited extent of playback-head losses over the audio range involved, no playback treble boost is incorporated.

Some recordings are still being made at 30 ips, and in this case the playback bass boost is sometimes a 6-db-per-octave slope throughout the audio range, except for a leveling off at the very low end. In other words, the turnover frequency for recorded flux may be outside the audio range at 30 ips. As for the 1.875-ips speed, which is sometimes used for reproduction of speech or music of limited quality, equalization patterns vary, but they may be assumed to resemble that of Fig. 611, but with still lower turnover frequencies.

equalization circuits

EQUALIZATION requirements in a tape recorder can be fairly formidable in terms of the amount of bass and treble boost required. If the response is to be reasonably flat over all or most of the audio spectrum, the designer must consider the maximum equalization required, the point at which bass or treble response begins to rise (turnover frequency) and the shape of the response characteristics. There are a variety of equalization circuits. The choice is governed not only by the considerations just listed but also by the manner in which these circuits affect distortion and high-frequency response.

One chapter cannot present all the equalization networks found in various tape recorders. What will be attempted instead is to cover adequately the *basic* circuits and some of their popular commercial variations and to explain in basic terms how they work.

The discussion, in part, will be divided between record and playback equalization. Each will present treble- and bass-boost circuits commonly found in tape recorders. Let us begin by examining some general principles of equalization.

In the accompanying figures some of the values shown are rounded for ease of illustration.

General principles

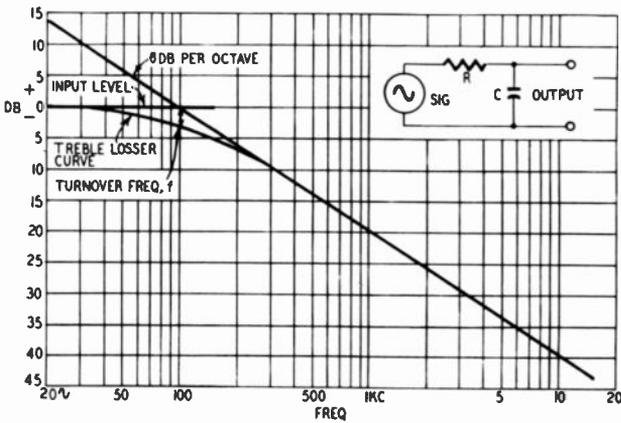
Fundamentally, equalization is of two sorts, *losser* or *feedback*.¹

¹ For excellent discussions of the subject, the reader is referred to the chapters on equalization in the following books: *High-Fidelity Circuit Design* by Norman H. Crowhurst and George Fletcher Cooper; *Understanding Hi-Fi Circuits* by Norman H. Crowhurst. Published by Gernsback Library, Inc.

Losser equalization is in the nature of a high- or low-pass filter; the desired frequencies go unattenuated from one amplifier stage to the next while the less desired ones are attenuated by being blocked or shunted to ground. Feedback equalization operates by controlling the gain of an amplifier stage; negative feedback is applied for all frequencies, but more so for the undesired ones, thus reducing gain for the latter.

Losser circuits

Figs. 701 and 702 show two basic losser circuits, a treble and a bass losser, respectively. Also shown are the response curves produced by each. These are called R-C curves because they are pro-



Example: $R = 100,000$ ohms; $C = .016 \mu\text{f}$; $f = 100$ cps $= \frac{1}{2\pi RC}$

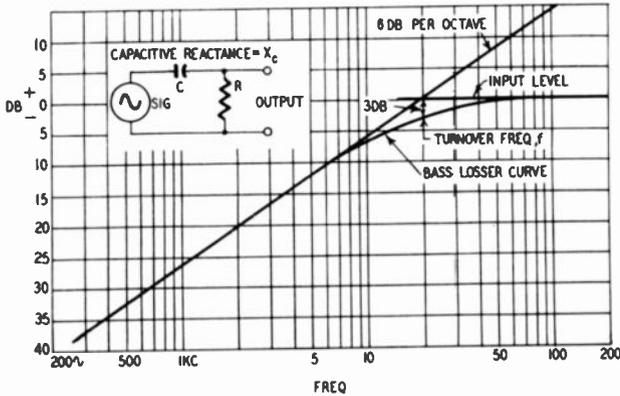
Fig. 701. Treble droop produced by an R-C losser circuit.

duced by resistance and capacitance. Looking at Fig. 701, the following should be noted:

1. High frequencies are attenuated because X_c , capacitive reactance, becomes smaller as frequency increases. R and X_c essentially form a voltage divider and, as frequency rises, the output voltage across C becomes a smaller portion of the input voltage.

2. The turnover frequency f is the point at which the values of R and X_c are equal. There is a 3-db difference between the output voltage at this point and the flat region. The turnover frequency and 3-db point are synonymous.

Given R and C , the turnover frequency is obtained by the formula $f = \frac{1}{2\pi RC}$, where f is cycles per second, π approximately 3.14, R in ohms and C in farads. The turnover point has meaning not only in mathematical terms but also in everyday experience because differences in sound level ordinarily are appreciable



Example: $R = 100,000$ ohms; $C = .0008 \mu\text{f}$; $f = 20,000$ cps $= \frac{1}{2\pi RC}$

Fig. 702. Bass droop produced by an R-C lossy circuit.

only when they exceed 3 db (although they may be *detectable* when they exceed 1 or 2 db). The product RC is referred to as the time constant (the time required to charge C through R to 0.636 of maximum voltage or to discharge C through R to 0.364 of original voltage).

3. Several other formulas relate frequency f , resistance R , capacitance C and capacitive reactance X_c to each other. Since R and X_c are equal at the turnover frequency, these terms can be substituted for each other. Useful variations of the basic formula are:

$$R = \frac{1}{2\pi fC}$$

$$C = \frac{1}{2\pi fR}$$

4. Above the turnover frequency, the curve conforms to what is called a 6-db-per-octave characteristic. The phrase "proportional characteristic" might be more descriptive. That is, the change in output voltage is exactly proportional to the change in frequency. This relationship may be direct or inverse. In Fig. 701, it is in-

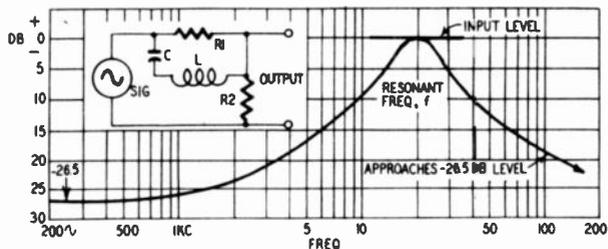
verse. As frequency goes up, output declines proportionately. When frequency doubles, the output is cut in half. Since a doubling in frequency corresponds to one octave and since halving the voltage output corresponds to a 6-db change, the linear portion is called a 6-db-per-octave characteristic.

5. In the vicinity of the turnover frequency, an R-C response curve changes by, or has a "slope" of, less than 6 db per octave. A couple of octaves are required on either side of the turnover point before the slope reaches 6 db per octave or flattens out. Going in the direction of the 6-db-per-octave portion, there is a 4-db decline in the first octave beyond the turnover frequency, a 5-db decline in the second and a 6-db decline thereafter. Going in the direction of the flat portion, there is a rise of 2 db in the first octave, nearly 1 db in the second and none thereafter. Fig. 702 is a mirror image of Fig. 701. The high frequencies get through the capacitor easily, while low frequencies do not. R and X_c essentially form a voltage divider and, as frequency declines, the output voltage across R becomes a smaller portion of the input voltage. The formulas for calculating turnover frequency, resistance or capacitance are the same as those listed earlier.

Theoretically, an inductance (L) could be substituted for the capacitance in Figs. 701 and 702 to obtain similar effects. The basic formula would be $f = 2\pi RL$. The R-L response curves would be just the opposite, however. For example, if an inductance were substituted in Fig. 701, the response characteristic would be that shown in Fig. 702 because the reactance of the coil increases with rising frequency, instead of declining as in the case of a capacitor. However, R-L circuits are only of academic interest for tape recorders. Various factors make the use of inductors impractical in this application: Inductors are expensive, may pick up hum, are relatively fragile and have some resistance which produces losses and prevents response curves from having the degree of precision that can be produced by R-C networks.

On the other hand, R-L-C (resistance-inductance-capacitance) networks are often used when the desired shape of the equalization curve is steeper than a 6-db-per-octave characteristic. The R-L-C combination provides the well-known sharply rising characteristic of a tuned circuit, as shown in Fig. 703. R1 and R2 form a voltage divider, R2 being considerably smaller, so that over most of the audio range the output voltage is appreciably less than the input voltage; the maximum amount of this attenuation is termed "insertion loss."

However, at the resonant frequency, the impedance of L and C in series becomes very small and bypasses R1. R2 becomes the larger leg of the voltage divider, and output voltage rises rapidly. Since the output declines again on the other side of resonance, the R-L-C network is used only at one end of the audio spec-



Example: $R_1 = 200,000$ ohms; $R_2 = 10,000$ ohms;
 $L = 20$ mh; $C = .0032$ μ f; $f = 20,000$ cps =
 $\frac{1}{2\pi\sqrt{LC}}$; insertion loss = $\frac{R_2}{R_1 + R_2} = \frac{1}{21} = 26.5$ db

Fig. 703. Response of an R-L-C circuit.

trum, almost always the treble end. Given L and C, the resonant frequency is obtained by the formula:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

By transposing terms, L or C can be determined when the frequency and either C or L is given. Thus:

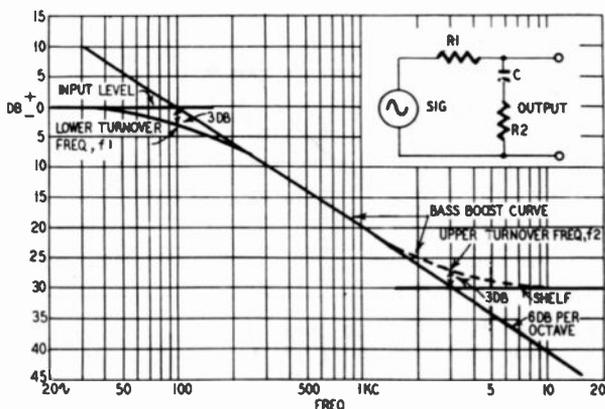
$$C = \frac{1}{(2\pi f)^2 L} \quad L = \frac{1}{(2\pi f)^2 C}$$

The sharpness of the resonant peak depends upon the relative values of L and C compared to R1.

Continuing this discussion, but returning to the R-C lossier networks, the basic circuits in Figs. 701 and 702 may be combined in various ways to produce more complex curves. Figs. 704 and 705 show two complex curves of fundamental importance. Whereas the curves of Figs. 701 and 702 have a continuing decline at either the treble or bass end, this is often undesirable in practical circuitry. The designer usually wants to shape the curve more exactly; he wants it to level off at both an upper and a lower frequency as in Figs. 704 and 705, not just at one end or the other as in Figs. 701 and 702.

Fig. 704 may be viewed as a bass-boost curve for tape recorder applications, although in other situations it might be called treble

droop. In broad terms, R_1 and C correspond to R and C in Fig. 701, and their effect is portrayed by the solid portion of the response curve in Fig. 704. C and R_2 account for the dashed portion. At very high frequencies, the equivalent circuit is a voltage



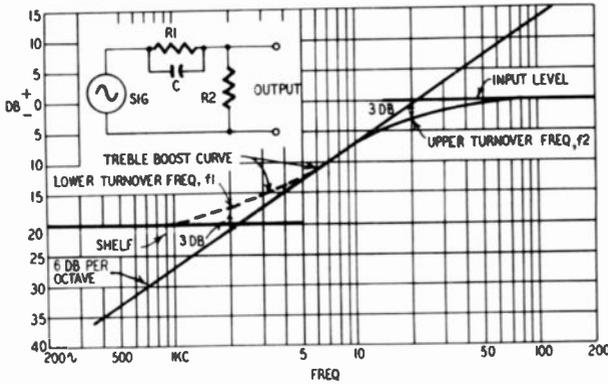
Example: $R_1 = 100,000$ ohms; $R_2 = 3,300$ ohms; $C = .016 \mu\text{f}$; $f_1 = 100$ cps $= \frac{1}{2\pi(R_1 + R_2)C}$; $f_2 = 3,000$ cps $= \frac{1}{2\pi R_2 C}$; insertion loss $= \frac{R_2}{R_1 + R_2} = \frac{1}{31} = 30$ db

Fig. 704. Bass boost produced by an R - C lossy circuit.

divider comprising R_1 and R_2 . Hence a limit is set to the maximum drop in high-frequency response; this maximum drop is referred to as the "insertion loss." The lower limit to which gain declines may be referred to as a "shelf." As the frequency declines from the upper extreme, the reactance of C , namely X_c , approaches that of R_2 ; at the upper turnover frequency designated as f_2 , R_2 and X_c are equal and output is 3 db above the shelf. As frequency declines further, X_c increases and the output goes up by voltage-divider action until the value of X_c approaches that of R_1 . When X_c becomes equal to $R_1 + R_2$ (at a relatively low frequency), the output voltage is within 3 db of the input voltage and a further rise is therefore very limited. In most instances R_1 is much bigger in value than R_2 so $R_1 + R_2$ is essentially determined by the value of R_1 .

The circuit of Fig. 705 may be viewed as treble boost. Broadly, R_2 and C correspond to R and C in Fig. 702 and account for the solid portion of the response curve in Fig. 705. At very low fre-

quencies, the equivalent circuit is a voltage divider comprised of R1 and R2, the latter forming a shelf at the low end. As the fre-



Example: $R_1 = 1 \text{ megohm}$; $R_2 = 110,000 \text{ ohms}$; $C = 80 \mu\text{f}$; $f_1 = 2,000 \text{ cps} = \frac{1}{2\pi R_1 C}$; $f_2 = 20,000 \text{ cps}$

$$= \frac{R_1 + R_2}{2\pi(R_1 R_2)C}; \text{insertion loss} = \frac{R_2}{R_1 + R_2} = \frac{0.11}{1.11} = 20 \text{ db}$$

Fig. 705. Treble boost produced by an R-C losser circuit.

quency increases, X_c declines and at the turnover frequency the reactance of C is equal to R1 and the output voltage is 3 db above the shelf. As X_c declines further with increasing frequency,

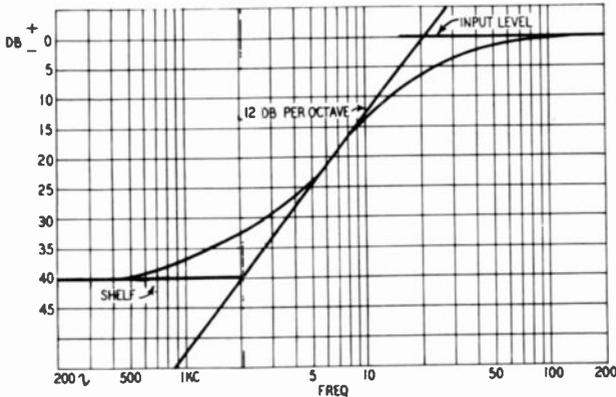


Fig. 706. Treble boost produced by using circuit in Fig. 705 in two amplifier stages.

the voltage-divider action of X_c and R2 causes the output across R2 to increase. However, this increase approaches a halt when

$X_c = \frac{R_1 R_2}{R_1 + R_2}$, (R_1 and R_2 in parallel), at the turnover frequency f_2 ; the output is then within 3 db of the input voltage.

The R-C combinations discussed thus far approach 6-db-per-

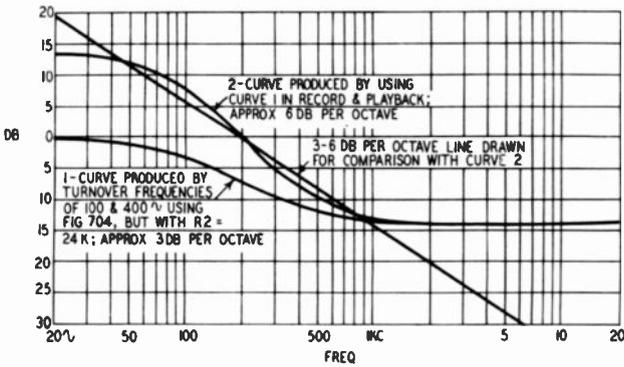


Fig. 707. Response curve having a slope of about 3 db per octave.

octave characteristics. However, several similar R-C networks may be cascaded (that is, used in series or in successive amplifier stages) to obtain more steeply rising or falling characteristics. The maximum rate of rise or fall is a multiple of the number of R-C networks used. A characteristic curve approaching 12 db per octave, produced by using the same R-C circuit in two amplifier stages, is illustrated in Fig. 706.

On the other hand, it may be desired to obtain a curve which rises or falls less than 6 db per octave. This can be done, over a limited span, by bringing the upper and lower turnover frequencies close together so that the response characteristic does not cover a sufficient number of octaves to attain a 6-db-per-octave slope. Curve 1 in Fig. 707 illustrates a response curve with a slope of about 3 db per octave obtained in this manner.

Feedback

The basic principle of feedback is simple. All other factors remaining the same, the gain of a tube is constant. The input is the voltage between control grid and cathode. Regardless of the signal impressed between grid and ground, it is the potential between grid and cathode that counts. Therefore, effective input can be reduced in two basic ways: (1) by applying to the grid a feedback voltage with a polarity opposite to the audio signal on the grid; (2) by applying to the cathode a feedback voltage

with the same polarity as the audio signal applied to the grid. If the cathode varies in the same direction as the grid, then the difference in voltage between grid and cathode is reduced, thereby cutting down the effective input.

Negative feedback falls into two basic categories: voltage feedback and current feedback. Although the same response curves can be obtained by either means, each type has distinctive characteristics which may or may not be desirable.

Voltage feedback

Voltage feedback—where feedback is obtained from the output voltage—is illustrated in Figs. 708 and 709. In Fig. 708, feedback is applied from plate to grid. Assume that the instantaneous sig-

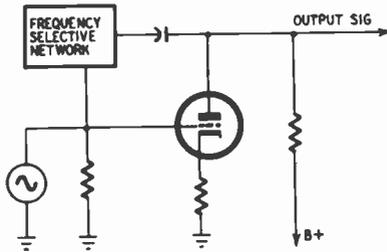


Fig. 708. Plate-to-grid voltage feedback.

nal voltage at the grid is positive. When the grid of a tube goes positive, its plate goes negative. Through the frequency-selective

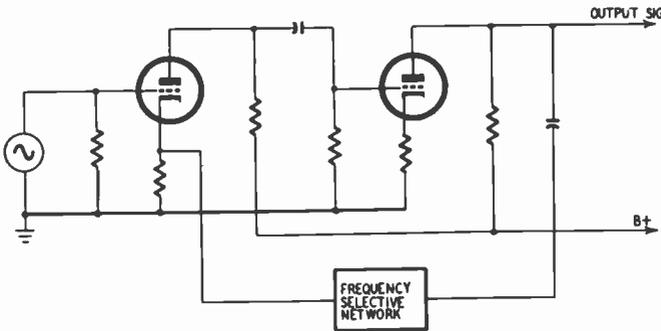


Fig. 709. Plate-to-cathode voltage feedback.

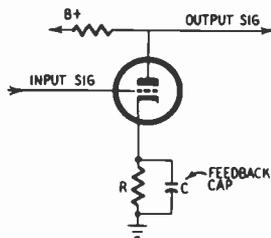
network, a fraction of the negative voltage at the plate is applied to the positive grid, reducing the net signal at the grid. Other sections of this chapter will discuss details of the frequency-selective network; it is sufficient here to state that R-C components

are usually employed, and turnover frequencies are determined in a manner akin to those in lossier circuits.

In Fig. 709, voltage feedback is shown applied to the cathode of the input tube. If the cathode polarity varies in the same direction as the grid polarity, the difference in voltage potential between the grid and cathode is reduced. Assuming that the instantaneous signal voltage at the grid of the input tube is positive, a positive voltage for feedback to the first cathode is obtained at the plate of the second tube. (Although the feedback signal polarity is positive, this should not be confused with the fact that the *type* of feedback is negative inasmuch as it is used to offset original input, or reduce gain.) The frequency-selective network is along the lines of that in Fig. 708.

Current feedback

By contrast, current feedback usually does not require connecting one tube element to another. The feedback voltage can be generated at the cathode by the simple expedient of using a



Lower turnover frequency (3 db rise in response) = $\frac{1}{2\pi RC}$; treble boost tapers off when the voltage across C becomes much smaller than the input signal voltage

Fig. 710. Treble boost by means of R-C current feedback.

relatively large cathode resistor and omitting the bypass capacitor. Assume the instantaneous signal voltage at the grid is positive, causing increased current to flow in the tube. This current goes through the cathode resistor. The increased current through the cathode resistor causes a larger voltage to appear across it. Since the electron flow is from ground to cathode, the cathode becomes more positive with respect to ground. In sum, when the grid

goes positive, the cathode also goes more positive and, as already stated, if the polarity at the cathode varies in the same direction

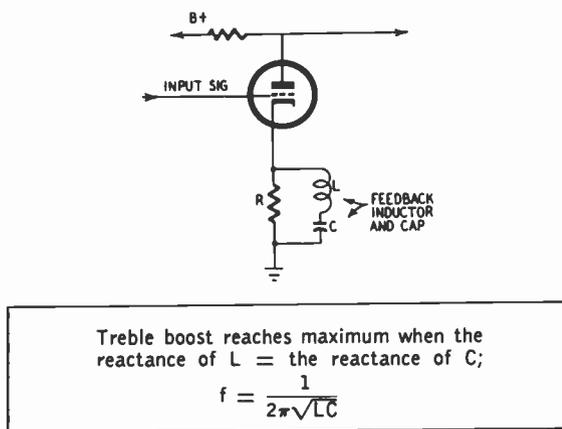


Fig. 711. Treble boost by means of R-L-C current feedback.

as the signal at the grid, the effective input is reduced. The larger the resistance (or reactance) between cathode and ground, the greater is the feedback and the lower the overall gain.

To achieve frequency equalization, the cathode resistor is bypassed so as to reduce feedback at those frequencies where higher gain is desired. Figs. 710 and 711 illustrate two basic methods of obtaining high-frequency boost by current feedback. In Fig. 710, a relatively small capacitor is used; its reactance relative to that of the resistor becomes small at high frequencies, where it serves to increase gain because the smaller the reactance between cathode and ground, the less feedback there is. The response curve resulting from the circuit in Fig. 710 tends to follow a 6-db-per-octave characteristic since it is formed by R-C components.

In Fig. 711, the feedback resistor is bypassed by an inductance and capacitance in series. This causes gain to rise sharply in the manner of a tuned circuit (and then to fall again on the other side of resonance).

Record equalization

Although tape recorders have incorporated varying concepts of how equalization should be achieved, there has been growing recognition of the fact that for optimum results treble boost should take place chiefly in record and bass boost chiefly in playback. NARTB equalization embodies this principle. Virtually all

professional machines and an increasing number of moderate-price ones are using NARTB equalization at 7.5 and 15 ips, and modified versions of it for different tape speeds.

Accordingly, this discussion shall in the main be oriented to the fact that record equalization calls for a substantial amount of

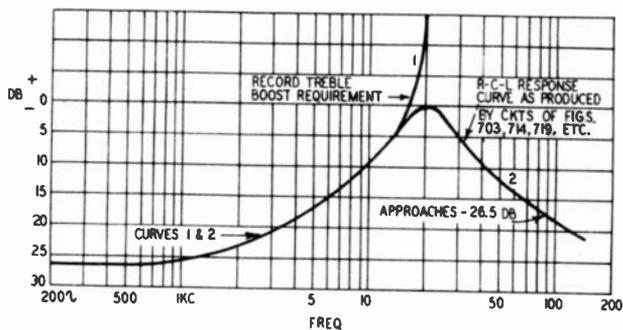


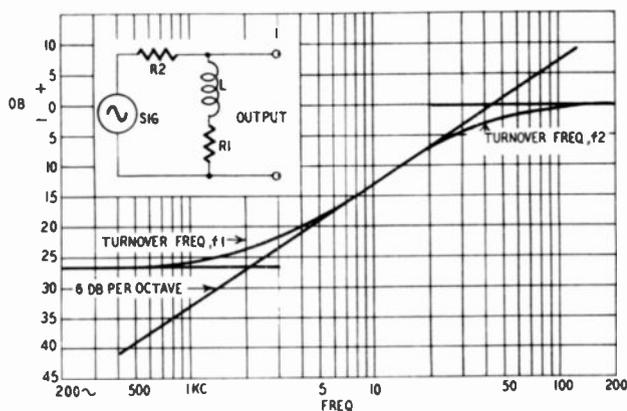
Fig. 712. Use of an R-L-C response curve to match record treble-boost requirement of a tape recorder operating at 7.5 ips.

treble boost and a slight amount of bass boost. But many recorders still use so-called half-and-half equalization, where half the treble boost is achieved in record and the other half in playback; and similarly for bass boost. It will be assumed, unless otherwise stated, that equalization is for the 7.5-ips speed, the lowest at which it is possible today to maintain relatively flat response out to 15,000 cycles.

Record treble boost

For recording more or less in conformity with the NARTB characteristic at 7.5 ips and at the same time using enough bias current to result in low distortion at high record levels, the required treble-boost curve must invariably have a slope greater than 6 db per octave over a sizable region if the frequency response is to be reasonably flat out to 10,000 cycles or beyond. This is because normal bias values together with other factors (principally demagnetization effect) result in a precipitous decline in the amount of signal recorded on the tape at high frequencies. Actually, record losses vary inversely with recorded wavelength: the higher the frequency and/or the slower the tape speed, the shorter the wavelength. Thus, in the attempt to get out to 15,000 cycles or nearly so at 7.5 ips, considerable record losses have to be overcome by treble boost.

The sharp treble boost required to satisfy the NARTB record characteristic, or modifications of it, may be had most conveniently by means of tuned R-L-C circuits. The required slopes can less easily be approximated by cascading several R-C



Example: $R_1 = 240$ ohms; $R_2 = 5,000$ ohms; $L = 20$ mh; $f_1 = 2,000$ cps $= \frac{R_1}{2\pi L}$; $f_2 = 40,000$ cps $= \frac{R_1 + R_2}{2\pi L}$; insertion loss $= \frac{R_1}{R_1 + R_2} = \frac{1}{21} = 26.5$ db

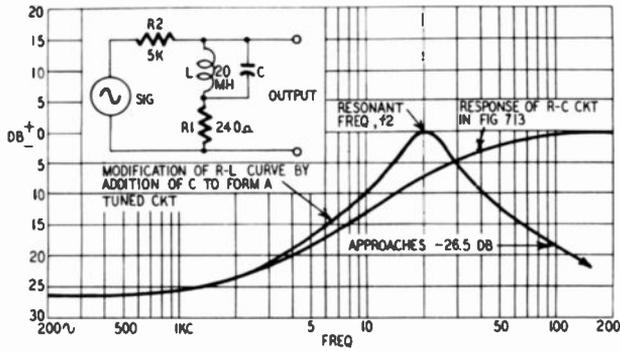
Fig. 713. Treble boost produced by an R-L losser circuit.

circuits. Although such cascading produces a boost considerably in excess of 6 db per octave, still the response curve does not rise as sharply as an R-L-C one.

Fig. 712 shows the response characteristic of a typical R-L-C curve as well as the hypothetical treble-boost requirement of a tape recorder. Curve 1 is the required treble boost out to 20,000 cycles, while curve 2 is the tuned-circuit characteristic. The steepness of the slope of an L-C tuned circuit is controlled by its Q (the ratio of the inductive reactance of the coil at the resonant frequency to the resistance of the coil).

The R-L-C circuit does not provide full compensation. Beyond 15,000 cycles, the two curves diverge: the R-L-C curve levels off while the required boost approaches a slope that is almost infinitely steep. However, out to the frequency of interest, assumed to be 15,000 cycles in Fig. 712, the two curves coincide so that the R-L-C circuit does what is necessary within the prac-

tical audio range. In some tape recorders, the maximum frequency of interest might be 12,000 or even 10,000 cycles at 7.5 ips, depending upon the designer's judgment as to what is the best compromise among the conflicting requirements of good treble response, low distortion and high signal-to-noise ratio.



Example: R_1 , R_2 , L and f_1 as in Fig. 713;
 $C = .0032 \mu\text{f}$; $f_2 = 20,000 \text{ cps} = \frac{1}{(2\pi f)^2 L}$

Fig. 714. Conversion of treble-boost curve in Fig. 713 into a tuned circuit characteristic (R-L-C curve).

Because the R-L-C curve can be easily tailored to coincide with the treble-boost requirement, it is ideally suited for record equalization. Let us see how a typical R-L-C treble-boost circuit of the lossier type can be so shaped.

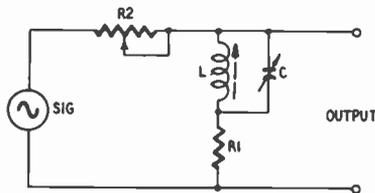


Fig. 715. Flexible version of circuit in Fig. 714. See Fig. 716 for the effects of varying R_2 , L or C .

Fig. 713 shows a treble-boost curve produced by an R-L circuit. R_1 and R_2 form a voltage divider, in which resistor R_1 determines the low-frequency shelf. The output voltage is 3 db above the shelf (turnover frequency) when R_1 and the reactance of L are equal. However, a rise faster than the 6-db-per-octave slope

produced by this circuit is needed. This can be had by placing a capacitor in parallel with L , producing a tuned-circuit response characteristic, as shown in Fig. 714.

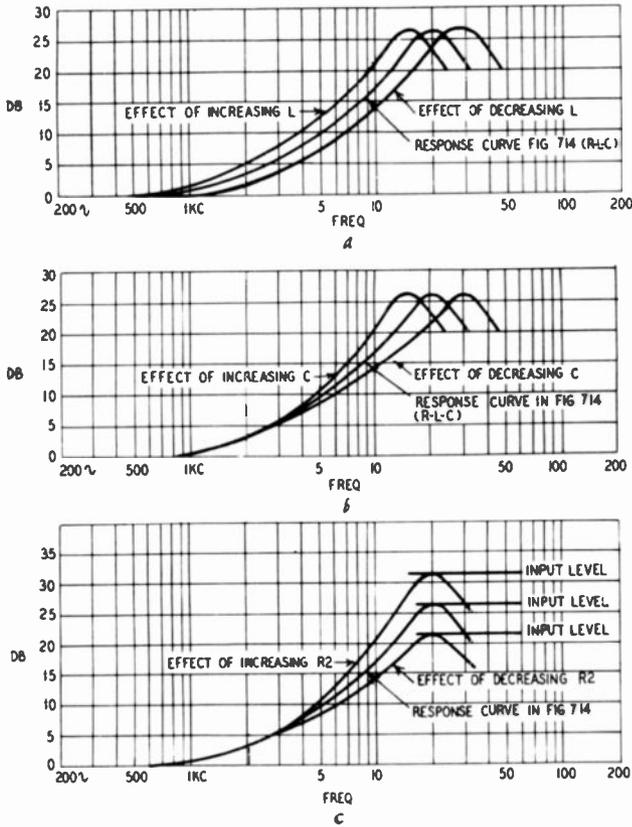


Fig. 716-a. Effect of varying L in Fig. 714; b) effect of varying C in Fig. 714; c) effect of varying R_2 in Fig. 714. Input levels are actually the same for all curves, but are shown differently for clarity of presentation.

Given L , the maximum response can be obtained at the desired frequency by choosing C in accordance with the formula mentioned earlier. By varying R_1 with respect to R_2 , maximum gain can be varied; that is, the low-frequency shelf can be changed. By varying L with respect to R_1 , the point at which treble boost begins (turnover frequency) can be controlled. For example, if L is reduced, its reactance equals R_1 at a higher frequency. However, as L is varied to shift the turnover frequency, C must also be adjusted if it is desired to maintain maximum response at the same frequency. If these two measures are taken simultane-

ously, the slope of the treble-boost curve becomes either more or less steep.

Fig. 715 is a modified version of Fig. 714, the difference lying only in the fact that all components but R_1 are made variable so that gain, slope and frequency of maximum response can be adjusted. Fig. 716 shows the effects of varying one element at a time. Fig. 716-a shows that as L is changed, not only does the frequency of maximum response shift, but so does the turnover frequency. Fig. 716-b shows that if C alone is varied, the rise in response begins at the same point and only the frequency of maximum response is affected. Fig. 716-c shows that as R_2 is varied, the gain of the response curve changes. Actually, the peak level at resonance stays constant and it is the shelf that changes level, but the presentation in Fig. 716-c illustrates the effect better.

Although networks as flexible as that of Fig. 715 have been incorporated in some custom recorders, fortunately in commercial practice a smaller number of adjustments, usually one, suffice. If a manufacturer were to use the circuit of Fig. 715 during the design stage of a recorder, by calculation and experiment he would ascertain the necessary values for each component in the boost network, taking into account the rest of the amplifier circuit, the tape he recommends and the optimum bias value. Thenceforth he could build the boost circuit with fixed values of resistors, coil

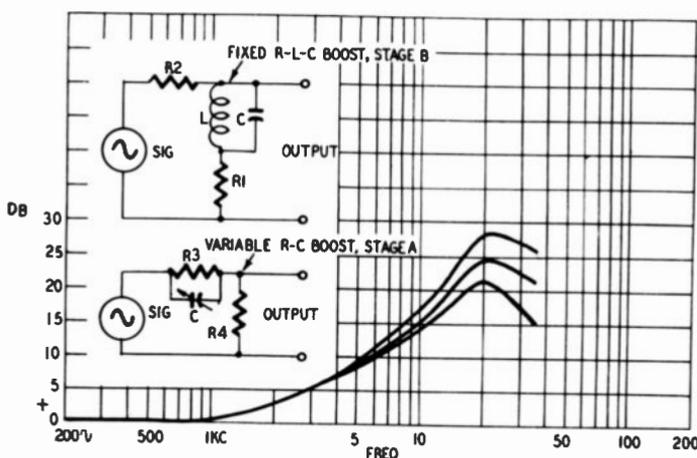
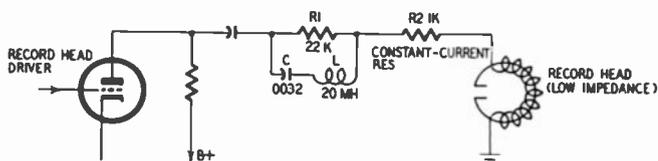


Fig. 717. Variations in total response produced by variable R-C treble boost plus fixed R-L-C treble-boost circuits in separate amplifier stages.

and capacitor, as in Fig. 714. To permit some flexibility, he might leave one of the components variable.

A frequent practice is to introduce variability in a separate circuit which helps shape the total treble-boost characteristic. For example, the circuit shown in Fig. 705 often provides part of the required treble boost. In this case, a certain amount of flexibility can be had by making the capacitor in Fig. 705 variable; a padder type capacitor is often used, yielding response variations as shown in Fig. 717.

The question of flexibility in the treble-boost characteristic is important. In almost all moderate-price recorders, and occasionally in professional ones, there is no equalization adjustment. This would be fairly reasonable if, as was the case until a few years ago, response were expected to extend only to a recorded wavelength of 0.001 inch. At 7.5 ips this translates into a frequency of 7,500 cycles, and at 15 ips into a frequency of 15,000 cycles. But improved playback heads (narrower gaps) and improved tapes (better high-frequency response) have raised expectations to 15,000 cycles at 7.5 ips. At this speed, however, record losses on the tape



$$f_r \text{ (resonant frequency)} = \frac{1}{2\pi\sqrt{LC}} = 20,000 \text{ cps}$$

Fig. 718. Example of treble boost produced by an R-L-C losser circuit.

beyond 7,500 cycles are still so severe as to require a large amount of equalization as well as careful setting of bias current because treble losses vary directly with bias. To record to 15,000 cycles at 7.5 ips requires far more accurate adjustment of equalization and bias than if 7,500 cycles were the upper limit. Therefore, if optimum results are to be had from a 7.5-ips tape recorder, one of these results being substantially flat response to 12,000 or 15,000 cycles, it is highly desirable that treble boost be adjustable. (The same applies to bias current.)

Fig. 718 shows an R-L-C treble-boost circuit of the losser type. Maximum boost is determined by the relationship between R1 and R2, which form a current-limiting resistance. At low frequencies, current to the record head is a small fraction of maxi-

imum possible current because R1 is fairly large. But at high frequencies the impedance of L and C in series becomes low enough to bypass R1, thus decreasing the series impedance and increasing current to the head. Minimum impedance occurs at the L-C resonant frequency. This is 20,000 cycles for the values given in Fig. 718, so that the lower slope of the resulting response curve matches the treble-boost requirement.

Turning to feedback circuits, Fig. 719 shows a popular R-L-C treble-boost network. An unbypassed cathode resistor produces feedback, the amount depending upon the value of the resistor.

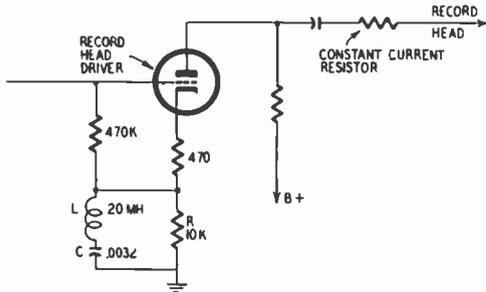
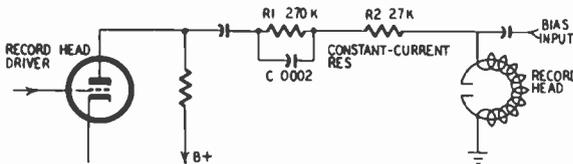


Fig. 719. Example of treble boost produced by R-L-C current feedback.

In Fig. 719, feedback is principally due to R. (The reason for connecting the grid resistor to the intersection of the 470- and 10,000-ohm resistors is to place the grid at the proper negative dc



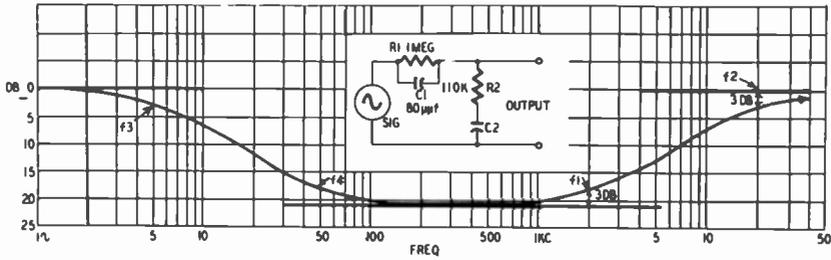
$$f_1 \text{ (lower turnover)} = \frac{1}{2\pi R_1 C} = 3,000 \text{ cps; } f_2 = 31 \text{ kc} = \frac{R_1 + R_2}{2\pi C R_1 R_2} . \text{ The response curve is similar to Fig. 705.}$$

Fig. 720. Example of treble boost produced by an R-C lossy circuit.

bias voltage relative to the cathode for linear operation of the tube. If the grid resistor went to ground, the cathode would be

at an excessive dc positive voltage relative to the grid. This is the same as saying that the grid would be at an excessive negative potential relative to the cathode.) At high frequencies, the series impedance of L and C becomes low and serves to bypass R, thus decreasing feedback and increasing gain. Maximum gain occurs of course at the resonant frequency of L and C when they present a virtual short circuit across R.

The advantage of using a negative feedback circuit, such as Fig. 719, is that feedback serves to reduce distortion. In other words, to the extent that the tube introduces distortion products (frequencies) not originally present in the audio signal, these products are added to the input signal in opposite phase, so as to largely cancel those produced in the tube. Distortion reduction is greatest at low frequencies because feedback is greatest in that region. However, this does not mean greater distortion at high frequencies for two reasons: (1) There is still some distortion-reducing feedback at all frequencies due to the 470-ohm resistor. (2) Typical audio sources contain the least audio energy at the highest frequencies. Since distortion declines with decreasing



Example: R1, R2, C1, f1 and f2 as in Fig. 705; C2 = .03 μ f; f3 = 5 cps; f4 = 50 cps. C1 corresponds to C in Fig. 705.

Fig. 721. Combined treble and bass boost produced by R-C lossy circuit.

signal amplitude, there is less need for measures against distortion in the treble range.

Let us now consider some typical R-C treble-boost circuits. Fig. 720 shows a lossy circuit. R2 is the constant-current resistor; its value is greater than the reactance of the record head at all audio frequencies so that, assuming for the moment R1 is out of the circuit, R2 essentially determines the amount of audio current through the record head. R1 is much larger than R2.

Consequently, at low frequencies current through the head is considerably reduced owing to the current-limiting action of R1. As frequency increases, C bypasses R1, resulting in greater audio current through R2 and the head. Audio current begins to rise at the turnover frequency determined by R1 and C. Its rise approaches a halt at the turnover frequency determined by C and

$$\frac{R1R2}{R1 + R2}$$

The response curve produced by this circuit results in almost a 6-db-per-octave treble boost. A more sharply rising characteristic is necessary if the response is to extend satisfactorily beyond 10,000 cycles. There are several possible answers to this situation:

(1) The recordist may be trying to achieve satisfactory response only to about 8,000 cycles. (2) The recorder may be using a sub-normal amount of bias current. This reduces the treble-boost requirement but at the same time results in greater distortion. (3) The recorder may have additional treble boost at other stages. For example, at one or more tubes there may be treble boost due to use of a small capacitor across a cathode resistor (Fig. 710).

At this point, a flag of caution should be waved with respect to turnover frequencies when R-C feedback circuits are used. R-C feedback circuits *do not necessarily* give the precise turnover characteristics that R-C lossier circuits do. A simple R-C lossier circuit requires about two octaves for response to depart 3 db from a flat course, and it takes another two octaves before response changes at the rate of 6 db per octave. In the case of R-C feedback circuitry, however, unless proper conditions are established, the shift from the region of maximum response to a falling characteristic may be either sharper or more gradual, depending upon the feedback circuit.

Record bass boost

In professional tape recorders, a few db of record bass boost are often introduced at the very low end to satisfy NARTB requirements. Moderate-price tape recorders may also provide a small amount of record bass boost for the same reason or they may contain a relatively large amount because the total bass-boost requirement is evenly split between record and playback.

Where only a small amount of record bass boost is required, the circuit is almost invariably of the lossier type. Where large amounts are used, either a lossier or feedback type is used.

Fig. 704 has shown the fundamental bass-boost loser circuit; the manner of its behavior has already been described. For the curve to follow a 6-db-per-octave slope to a given frequency, say 50 cycles, the bass boost must continue to a much lower frequency, otherwise the curve will begin to level off in the region of 50 cycles. The further that bass boost continues, the greater the loss of gain involved; after all, bass boost is obtained in a roundabout way, by attenuating all the other frequencies. But if some lack of precision in the bass-equalization characteristic is acceptable, then bass boost need not be carried to an inordinately low frequency, and gain, perhaps as much as 10 db of it, can be saved. Gain requires amplifier stages and costs money.

$$f_3 = \frac{1}{2\pi C_2 \left[\frac{R_3(R_1 + R_2)}{R_1 + R_2 + R_3} \right]} = 17.5 \text{ cps}$$

$$f_4 = 50 \text{ cps}$$

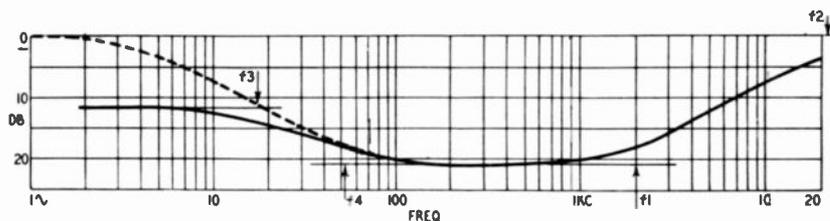
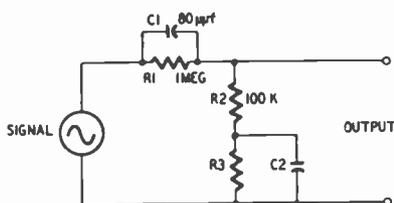


Fig. 722. Modification of response curve in Fig. 721 to produce less bass boost below 20 cycles. The dashed line is the response in Fig. 721.

$$R_3 = \frac{1}{(2\pi)(20) \left(\frac{.032}{10^6} \right)} = .25 \text{ meg}$$

$$C_2 = \frac{1}{2\pi f_4 \left(\frac{R_2 R_3}{R_2 + R_3} \right)} = .045 \mu f$$

R_1, R_2, C_1 as in Figs. 705 and 721.

R_3 chosen on approximate basis to equal reactance of C_2 in Fig. 721 at 20 cps.

On the other hand, it is often possible to eat one's cake and have it too when it comes to bass record equalization. Record treble equalization involves a large sacrifice of gain, and some of this gain can be recouped as bass boost if the treble and bass-boost circuits are combined. In such a case, full bass boost can be preserved without any sacrifice in precision. Fig. 721 is a typical illustration of such a combined circuit. Except for the

addition of C2, this figure is the same as Fig. 705 and operates in the manner already described so far as treble boost is concerned. C2, R1 and R2 supply bass boost in accordance with the explanation of the circuit of Fig. 704.

However, it will be noticed that bass and treble boost in Fig. 721 are of the same amount whereas, at least to the maximum and minimum frequencies of interest, say 15,000 and 50 cycles, less bass than treble boost is desired when recording. Thus bass boost in Fig. 721 extends to the extreme low end, perhaps to 5 cycles. In other words, the reactance of C2 does not become as

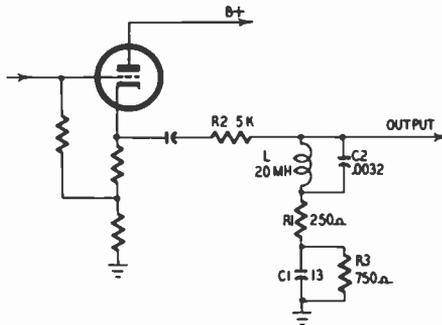


Fig. 723. Addition of bass boost to treble-boost circuit in Fig. 714. A cathode follower is required because of the low impedance (about 5,000 ohms) of the equalizer network at mid-frequencies.

large as R1 until 5 cycles, at which point bass boost approaches a halt. But it is undesirable to have bass boost extend this far down because it serves only to emphasize rumble frequencies due to the tubes or input signal. To keep gain from increasing below, say, 20 cycles, it is necessary to prevent the reactance of C2 from causing further appreciable increase in the impedance of the output leg of the voltage divider. To do so, resistor R3 is connected across C2, as shown in Fig. 722. The illustration shows how R3 is calculated and its effect upon the bass turnover frequencies.

Fig. 723 shows another combination bass- and treble-boost circuit. In this case the bass-boost configuration of Fig. 722 is combined with the R-L-C treble-boost circuit originally shown in Fig. 714. Similarly, the bass-boost circuit can be combined with still other treble-boost networks.

Playback equalization

Whereas a large amount of treble boost and little or no bass

boost are generally required in record, the opposite is true in playback where a large amount of bass boost and little or no treble boost are needed. To a substantial extent, the same basic circuit configurations are used for playback as well as record; only the

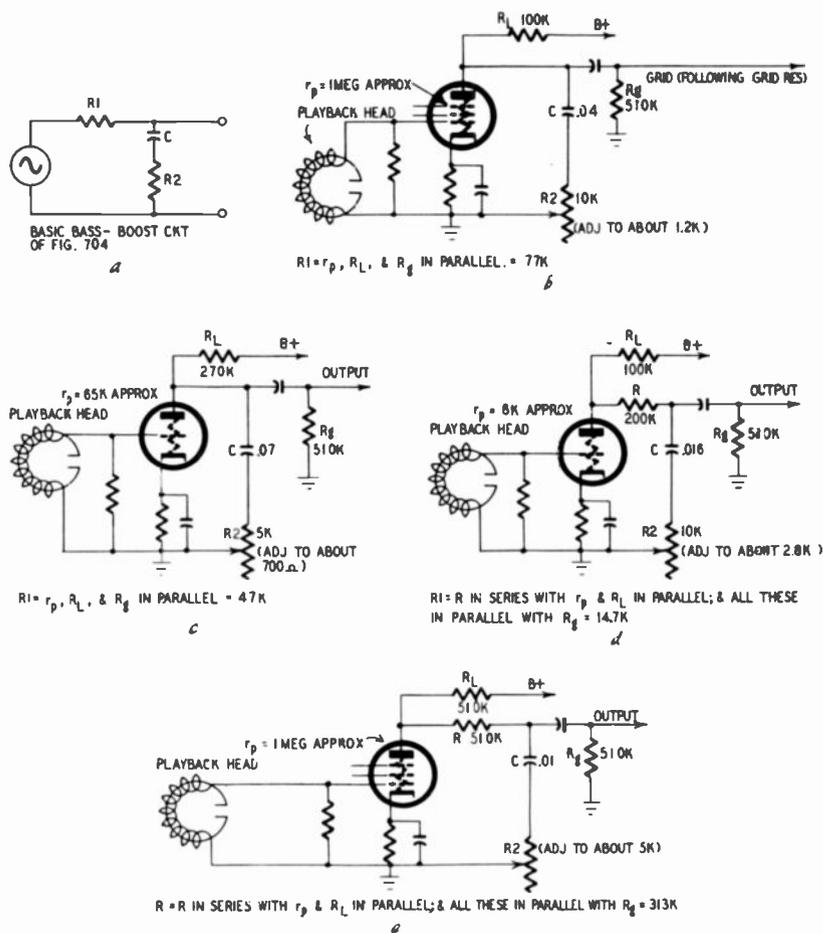


Fig. 724. Practical variations of the bass-boost circuit in Fig. 704.

values of the components differ. On the other hand, some equalization arrangements are more or less unique to the playback mode.

Playback bass boost

The playback head, being an inductive device, has an output

voltage proportional to the rate at which the magnetic field on the tape is changing; i.e., proportional to frequency. Thus, head output decreases 6 db per octave as frequency declines, and bass boost in very substantial quantity—36 db of it for NARTB equalization—must be introduced as a compensating measure. In this discussion, it will be assumed that NARTB equalization is used, which means that bass boost commences (3-db rise) at 3,180 cycles and approaches an upper shelf (3 db below maximum gain) at 50 cycles.

Since the declining output of the playback head essentially follows a 6-db-per-octave characteristic, the bass-boost curve must do likewise. R-C circuits, which possess such a characteristic, are therefore used for playback bass-boost circuits, whether of the lossy or feedback type. In feedback circuits, only the voltage feedback type is employed. Use of current feedback, namely that produced by a large cathode resistor, would necessitate bypassing the resistor with an inductor to achieve bass boost, a practice that is objectionable because of the disadvantages of inductors in such use (hum pickup, cost, fragility, lack of precise equalization).

Fig. 724-a repeats the fundamental bass-boost lossy circuit of Fig. 704, while parts b through e present several versions of a. Each variation has its points of interest.

In Fig. 724-b, R1 consists of the 100,000-ohm load resistor (R_L) in parallel with the much larger plate resistance of the tube (r_p), about 1 megohm, and with the following 510,000-ohm grid resistor (R_g). For easier visualization, Fig. 724-b is redrawn as an equivalent circuit in Fig. 725-a. The 77,000-ohm parallel resistance R1 (r_p , R_L and R_g in parallel) and 0.04- μ f capacitance determine approximately the lower turnover frequency, 50 cycles. R2, adjusted to about 1,200 ohms, and C determine the upper turnover frequency of 3,180 cycles. Fig. 724-c is essentially the same, except that here a triode is used. R1 is 47,000 ohms and is largely determined by the plate resistance of the tube, which in this case is assumed to be 65,000 ohms, considerably smaller than the 270,000-ohm plate load and grid resistors. R1 and C produce the lower turnover of 50 cycles. R2, which is variable, may be adjusted so that in conjunction with C it produces the upper turnover frequency of NARTB equalization, namely 3,180 cycles.

Ordinarily, triodes are considered preferable to pentodes as input tubes because as a rule they produce less hum and noise (although this rule has its exceptions). On the grounds of hum and noise, therefore, the circuit of Fig. 724-c might be preferred

to that of Fig. 724-b. On the other hand, a pentode has an important advantage over a triode in that its input capacitance is much lower, thus preventing loss of high frequencies. Thus, it might seem that with respect to frequency response the equalization circuit of the triode circuit is at a disadvantage.

However, this is not true in Fig. 724-c. Input capacitance consists mostly of that between plate and grid and in effect varies directly with gain due to Miller effect. (For example, when the grid goes positive, the plate goes negative; the more tube gain, the greater the negative voltage on the plate. The signal source sends a charging current into the grid-plate capacitance whose ability to absorb current from the input signal varies with the potential across this capacitance; hence the greater the gain, the more signal current is absorbed by plate-grid capacitance and the greater are the signal losses; this effect is equivalent to that produced by a larger capacitance between plate and grid than the actual physical capacitance.) In Fig. 724-c the equalizer capacitor C is a virtual short circuit at high frequencies and the load consists mainly of R2, a relatively small value. Since the load, principally R2, is in series with the plate resistance, by voltage-divider action there is very little output voltage across R2. In brief, gain of the tube is greatly reduced at high frequencies. Along with this reduction in gain there is a reduction in Miller effect. In other words, the input capacitance becomes very small and high-frequency response is not menaced.

Still, there is a slight disadvantage to the circuit of Fig. 724-c. To the extent that plate resistance departs from the nominal value of 65,000 ohms due to voltage changes, age or the individual tube used, the turnover frequency at the low end (in the region of 50 cycles) is affected. Thus, bass equalization will not be absolutely precise. However, this variation is usually of an order small enough to be acceptable for practical operation.

In Fig. 724-d the plate resistance of the medium- μ type of triode used is too low to serve as R1. Therefore, a 200,000-ohm resistor is used as the principal part of R1. R1 figures out to 147,000 ohms and in conjunction with the 0.018- μ f capacitor produces the desired turnover frequency of approximately 50 cycles. Potentiometer R2 is adjusted to about 2,800 ohms to produce a 3,180 cycle turnover frequency in conjunction with C.

Fig. 724-e is a similar configuration, except that a pentode is used. Although the load resistance in parallel with the plate resistance of the tube and with the following grid resistor is suf-

ficiently high to serve as R_1 , the designer has sought to reduce the effect of changes in plate resistance upon equalization by inserting R . Consequently, R_1 is determined to a substantial extent by the 510,000-ohm resistor R . The plate and load resistances are in parallel with each other (combined value about 330,000 ohms) and in series with R . All these are in parallel with the 510,000-ohm grid resistor, making a total resistance R_1 of 313,000 ohms. R_1 and the 0.01- μ f capacitor produce a turnover frequency close to 50 cycles. R_2 is adjusted to about 5,000 ohms to produce the upper turnover frequency of 3,180 cycles. (The equivalent circuit appears in Fig. 725-b.)

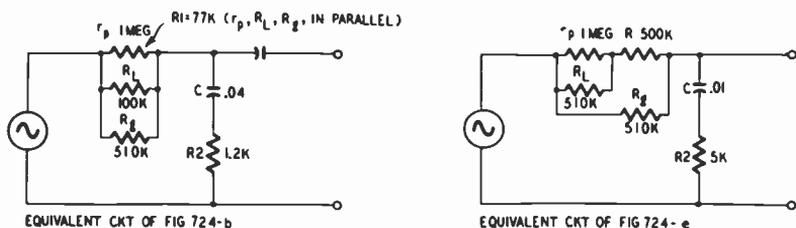


Fig. 725. Equivalent circuits for Fig. 724.

Feedback bass equalizers of the voltage type have two worthwhile advantages over lossier circuits: (1) reduction in distortion, particularly at the high frequencies, where signal output from the head is greatest; (2) reduction in the effective plate resistance of the tube and therefore in its output impedance; this facilitates maintenance of high-frequency response inasmuch as shunt capacitance (stray capacitance and capacitance of the following stage) produces less treble loss across a small resistance than a large one.

Why does negative voltage feedback reduce internal resistance of the tube? Assume, for example, that a decrease in the value of the load impedance, say due to stray capacitance, reduces the tube's output voltage. As a result, the feedback voltage also decreases, bringing the output voltage close to its original value. The same effect would be produced if the internal resistance of the tube were very small compared with the impedance of the load. So far as output signal is concerned, the internal resistance and external load are in series, forming a voltage divider, with the output voltage present across the load. Relatively large changes in the load can occur without affecting voltages across it, provided that the tube's internal resistance is low enough. With negative voltage feedback, the tube behaves as though it had a lower plate resistance.

A typical feedback bass equalizer with good characteristics is shown in Fig. 726. R_2 is relatively small and at high frequencies, where C is a virtual short circuit, a large amount of feedback is applied to the cathode of the first stage. R_2 , R_k , and C essentially determine the upper turnover frequency (3,180 cycles); as frequency decreases, the reactance of C becomes equal to R_2 and R_k , feedback starts decreasing and gain starts increasing. R_1 and C essentially determine the lower turnover frequency (50 cycles); as frequency continues to decrease, the reactance of C becomes equal to R_1 , C no longer by-passes R_1 , feedback stops increasing and the gain approaches a maximum. At very low frequencies the value of the coupling capacitor must be properly selected to avoid subsonic peaking due to feedback.

The roles of R_1 , R_2 and C in Fig. 726 correspond to those of the same components in lossier bass-boost circuits. However, the response curve may not be as precisely shaped by feedback as by

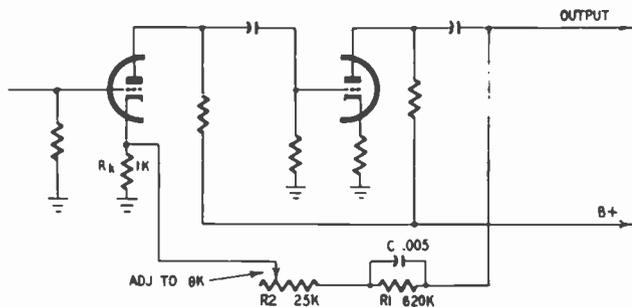


Fig. 726. Bass-boost circuit using voltage feedback over two amplifier stages.

lossier networks. That is to say, the shift from flat response to a 6-db-per-octave characteristic may be considerably more gradual in the case of a feedback equalizer. Fig. 727 shows a comparison between the bass boost achieved by an R-C lossier and an R-C feedback circuit. In both cases the turnover frequencies are nominally 50 and 3,180 cycles in accordance with NARTB playback equalization. Feedback may produce a more gradual transition from flat to 6-db-per-octave response at the very low end, so bass boost may suffer somewhat.

The more gradual turnover in a feedback equalizer is not a necessary condition, although one that is likely to occur at least to a moderate extent. To offset this lack of precision, the lower turnover frequency can be reduced to provide sufficient bass equalization within the frequency range of interest.

Feedback equalizers do not always display as sharp a turnover as lossier circuits because variation in gain does not vary purely with feedback. Instead, signal attenuation due to feedback is described by the expression $1 + A\beta$, where A is gain without feedback and β the fraction of the output voltage that is fed back. In Fig. 726 the maximum fraction of voltage feedback, which occurs at the high end, is determined by the ratio of R_k to $R_k + R_2$, C being a virtual short circuit at high frequencies. The minimum percentage of voltage feedback which occurs at the low end, is determined by the ratio of R_k to $R_k + R_1 + R_2$, C being a virtual open circuit at very low frequencies.

Although it is the intention of this book to minimize mathematical presentations, the importance of feedback and the simplicity of the arithmetic involved make it desirable to show why it is that attenuation due to feedback varies with the quantity of $1 + A\beta$. Let e be the input voltage to the amplifier, e_o the output voltage, A the amplifier gain without feedback and β the fraction of e_o fed back to the input. The output voltage equals amplifier gain times the voltage between grid and cathode. This is the input voltage minus the fraction of output voltage fed back. Gain in an amplifier is output voltage divided by input voltage or e_o/e .

$$e_o = A(e - \beta e_o) \quad (1)$$

$$e_o = Ae - A\beta e_o \quad (2)$$

$$e_o + A\beta e_o = Ae \quad (3)$$

$$e_o(1 + A\beta) = Ae \quad (4)$$

Rearranging the terms of equation 4, we find the expression for the gain of a feedback amplifier:

$$\frac{e_o}{e} = \frac{A}{1 + A\beta} \quad (5).$$

Now let us assume that the value of A is substantially greater than 1, so that 1 becomes an insignificant part of the denominator of equation 5 and can therefore be omitted. Thus:

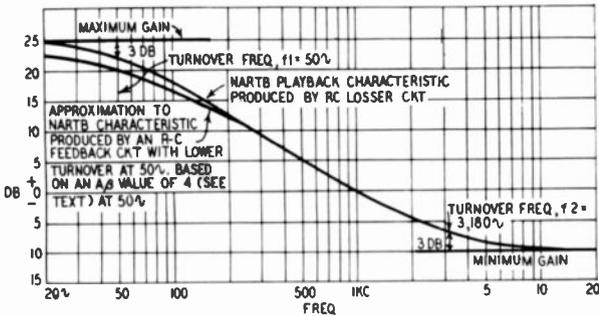
$$\frac{A}{1 + A\beta} \cong \frac{A}{A\beta} \cong \frac{1}{\beta} \quad (6)$$

($A\beta$ is much larger than 1.)

The gain of a feedback amplifier is inversely proportional to the feedback fraction (β) so long as $A\beta$ remains appreciably greater than 1. For practical purposes, values of $A\beta$ in excess of 4 are sufficient. (Addition of 1 to 4 makes 5, which is a difference of only 2 db.) Where a large amount of bass boost is required and β

becomes very small at the low frequencies, then the gain (A) must be high to maintain $A\beta$ above 4.

Assuming NARTB playback equalization, there must be a total of 36-db bass boost; 30 db of this occurs between 50 and 3,180 cycles, with low-frequency output tapering off to a level 3 db higher than at 50 cycles and with high-frequency output tapering off to a level 3 db lower than at 3,180 cycles. And 36 db of equalization is equal to a 63-to-1 voltage ratio. If the term $A\beta$ must be at least 4 at the low end of the frequency range, then at the high end it must be at least 63 times as great, or 252. Therefore, if β could be varied from 1 at the high end down to 0.016



$$f_1 = \frac{1}{2\pi R_1 C} = 50 \text{ cps}; f_2 = \frac{1}{2\pi C (R_2 + R_k)} = 3,180 \text{ cps}$$

Fig. 727. Comparison of bass-boost curves produced by R-C losser and feedback circuits.

(or 1/63) at the low end, an amplifier having a gain of 252 would suffice. At the low-frequency end, the term $A\beta$ would equal 4, namely the product of 252 times 0.016. However, it is not practical to have β as large as 1, chiefly because this would load the output heavily, producing distortion and excessively reducing gain at high frequencies. As can be seen in Fig. 726, if β were to become 1, this would mean that the feedback resistor R_2 would have to diminish to zero, leaving the cathode as the only significant portion of the load resistance (the reactance of C would be negligible at high frequencies).

For practical circuitry, therefore, β may not exceed about 0.1 without excessively loading the output of the amplifier. Consequently, the amplifier must have a gain of about 2,500 in order that the feedback fraction may vary from 0.1 to 0.0016 (a range of 63 to 1), without the term $A\beta$ becoming smaller than 4. This

will maintain satisfactory precision of the equalization characteristic and at the same time avoid undue loading of the amplifier output. Two stages of a high-mu triode, such as the 12AX7, can provide the needed gain.

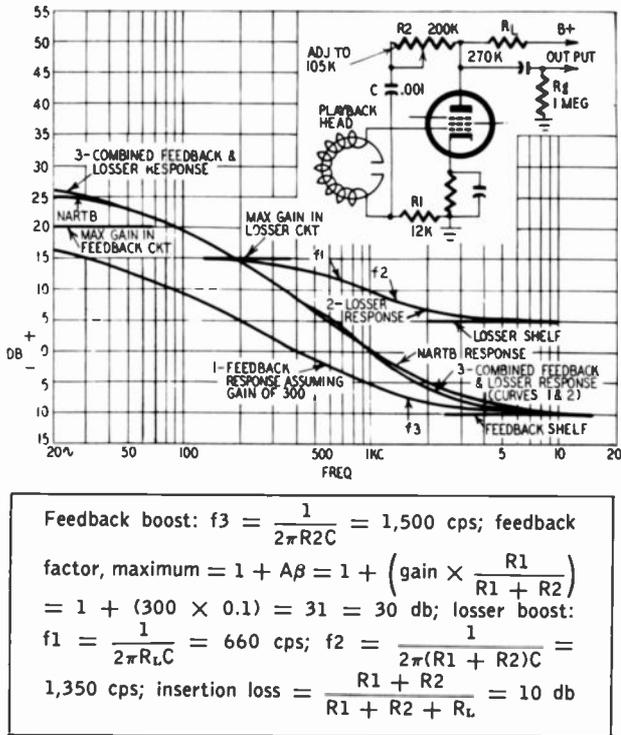
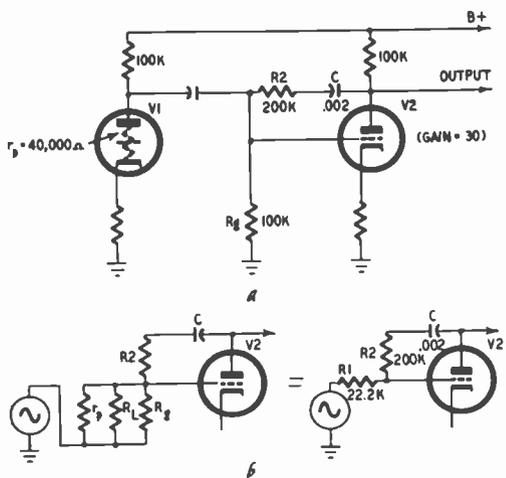


Fig. 728. Approximation of NARTB bass boost produced by plate-to-grid feedback combined with a losser circuit.

Using feedback, equalization satisfactorily approximating the NARTB characteristic can be achieved with a single pentode, even though the maximum gain from a pentode is only about 300 in practical circuitry rather than the 2,500 previously indicated as desirable. What is done is to combine a losser circuit with the feedback network so that the corresponding curves add up to a characteristic approaching NARTB equalization.

Fig. 728 illustrates such a circuit. R1, R2 and C constitute the feedback network, with R1 and R2 forming a voltage divider. As frequency declines, the reactance of C becomes equal to R2 and the feedback voltage across R1 begins to decrease, with a resulting increase in gain at the low-frequency end. The feedback curve shown in Fig. 728 has a turnover frequency of 1,500

cycles. The lossier circuit comprises $R_1 + R_2$ in series, R_L and C . It operates in the same manner as Fig. 724-b, with R_L playing the same role and $R_1 + R_2$ playing the role of R_2 ; the resulting curve has turnover points at 660 and 1,350 cycles. Addition of the feedback and lossier curves produces a characteristic close enough to the NARTB one for practical purposes.



$$\begin{aligned}
 f_2 \text{ (upper turnover frequency)} &= \frac{1}{2\pi R_2 C} \\
 &= 400 \text{ cps; bass boost tapers off at low} \\
 &\text{end as } A\beta \text{ (gain of } V_2 \text{ times fraction of} \\
 &\text{output voltage fed back) becomes much} \\
 &\text{smaller than 1; feedback factor, maximum} \\
 &= 1 + A\beta = 1 + \left(\text{gain} \times \frac{R_1}{R_1 + R_2} \right) \\
 &= 1 + (30 \times 0.1) = 4 = 12 \text{ db}
 \end{aligned}$$

Fig. 729. Interstage plate-to-grid feedback circuit producing bass boost.

Fig. 729 is an example of plate-to-grid feedback introduced after the input tube. This circuit produces bass boost with an upper turnover frequency of about 400 cycles, being used in a recorder with half-and-half equalization. The gain of V_2 produces a voltage at its plate 30 times that at the grid, but in opposite phase. Therefore C and R_2 , from the viewpoint of the grid circuit, have 31 times the grid voltage across them. This enables them to accept 31 times as much signal current. Thus the actual values of 200,000 ohms and .002 μf are equivalent to 6,500 ohms (200,000/31), and .062 μf ($31 \times .002$); these equivalent values are in shunt with the plate of V_1 and serve to load this tube in the same fashion as in Fig. 725-c.

A number of the playback bass boost circuits illustrated (Figs. 724;728) incorporate means for adjusting the response curve. This flexibility makes fairly precise equalization possible, at the same time allowing for the effects of other factors upon high frequencies. For example, if in playback there are some treble losses due to cable capacitance, then the upper turnover frequency f_2 can be reduced somewhat. This means that the equalization curve does not drop as much at the high end. Thus, where NARTB equalization is required, a turnover of, say, 2,000 cycles instead of 3,180 might approximately balance out high-frequency losses elsewhere in the playback amplifier.

Playback treble boost

To correct for playback losses (due to gap width, hysteresis, eddy currents), to compensate cable losses or to complete a particular equalization characteristic employed, tape recorders frequently provide high-frequency boost in the playback amplifier.

The shape of the required treble-boost curve will depend upon the factors which are primarily responsible for playback losses. If gap width is the predominant factor, then losses take place at a rapidly accelerating rate. Therefore a circuit with a sharply rising characteristic is needed. This may be obtained by an R-L-C circuit. Such a circuit can add half an octave or so to the high-end response of the tape recorder, usually a very worth-while addition.

One way of achieving this effect is to place a suitable capacitor across the playback head as shown in Fig. 730. The capacitor and the inductance of the head form a tuned circuit which can be made to resonate at the desired frequency by proper choice of the capacitor value. Voltage across the capacitor reaches a maximum approximately at resonance, and output voltage can therefore be appreciably increased, depending upon the Q of the tuned circuit. Although capacitance across the playback head in the form of cable, interwinding or input-tube capacitance is usually viewed as a threat to high-frequency response because of its shunting effect, yet properly controlled capacitance can produce just the opposite result. If the head and the various capacitances resonate within the audio range, then there are audio losses above resonance. But, if resonance occurs slightly beyond the audio range, then resonance can serve to improve the response at the upper end of the spectrum. If the peaking effect due to the tuned circuit is too great, it may be necessary to place a resistor across the

head to reduce the Q of the circuit and thereby the rise in response. If the recorder uses a head with a very narrow gap and operates at high speed, say 15 ips (so that gap losses do not enter into the picture) and if there are no treble losses due to other factors, then rising output due to head resonance might be undesirable. In such a case it would be necessary to make sure that head resonance occurs well above 20,000 cycles or use a resistor to reduce the Q of the resonant circuit.

The treble-boost techniques found in the record section are also often used for playback. For example, the treble boost may be associated with the bass-boost circuit (Fig. 722) where $C1$ bypasses

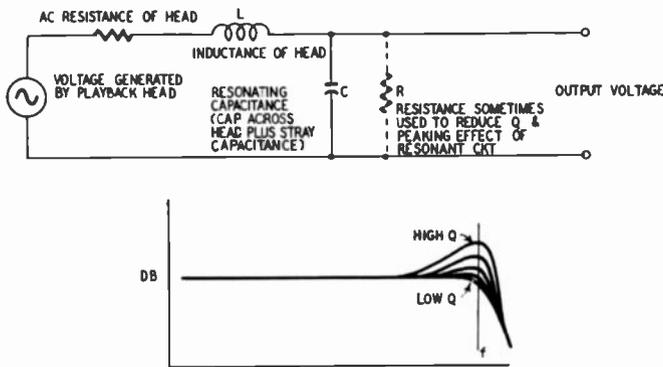


Fig. 730. Playback treble boost produced by resonating the playback head.

R1. Of course, for playback purposes, the values are different from this figure since playback calls for a large amount of bass boost and a small amount of treble boost.

Quite frequently, treble boost is achieved by current feedback as in Fig. 710, where the cathode is shunted by a capacitor, or as in Fig. 711, where the cathode is shunted by an inductor and capacitor in series, producing a much more sharply rising curve. The amount of current feedback, and thus the amount of treble boost which can be achieved by a capacitor or capacitor-inductor bypass, does not vary purely with the size of the cathode resistor. Instead it varies with the expression $1 + R_k g_m$, where R_k is the cathode resistor; g_m the transconductance of the tube in mhos. As long as the term $R_k g_m$ is large compared with 1, say four times as large or greater, feedback will vary essentially in direct proportion to the value of the cathode resistor.

Assuming that $R_k g_m$ is suitably large to begin with, feedback

begins to decrease and gain to rise appreciably when the reactance of the bypass element, say a capacitor, becomes equal to the cathode resistor. Above this frequency, the capacitor's reactance, being smaller than R_k , principally determines the ac voltage between cathode and ground, hence the amount of feedback.

oscillators

THE oscillator operates only when the tape recorder is in the record mode and usually has a double function—to provide bias current to the record head and erase current to the erase head. In recorders using a permanent magnet for erase or in special machines such as duplicators, where erasure is not needed, the bias function alone is performed.

Bias current is fed into the record head along with the audio signal current and serves two vital purposes. It increases the amount of signal which is recorded on the tape. At the same time, for a given level of recorded signal, it reduces distortion. Unfortunately, there is the disadvantage that, as bias current is increased above a certain point, high frequency response deteriorates. At the commonly used speeds of 15, 7.5, and 3.75 ips, the bias required for minimum distortion entails very substantial losses in the amount of high frequency signals recorded on the tape. The slower the tape speed, the greater are the treble losses.

Bias current requirements of record heads are usually fairly modest, on the order of 1 ma for many heads. In contrast, a typical erase head requires much more current to perform its function properly. Erase current may range from something like 15 ma to many times this amount.

Oscillator operation

The purpose of the grid resistor R and grid capacitor C2 in Fig. 801 is to provide the oscillator tube with the required negative

grid bias. The amount of grid bias depends upon the magnitude of oscillation required—within the tube's capabilities. When the grid goes positive and draws current, the resulting electron flow charges the top of the capacitor. The only path for the capacitor to discharge is through the grid resistor. As electrons leak slowly from top to bottom of the capacitor through the resistor, this flow causes a negative dc voltage to appear at the top of the resistor. This voltage also appears at the control grid.

The negative grid leak bias reduces the transconductance (g_m) of the tube, hence the gain around the complete oscillation loop. If the loop gain is greater than 1, as it must be for oscillation to start, the amplitude of each successive oscillation will be greater than the previous one. This causes the grid to swing more into the grid current region on each positive half cycle, resulting in more grid leak bias. But the bias affects the transconductance very markedly: the greater the negative bias, the lower the transconductance. So each positive grid swing results in added negative bias, reducing the transconductance, hence the gain, until the loop gain is exactly 1. The amplitude of the oscillations will remain at this value very closely. Suppose some disturbance occurred which would increase the amplitude of oscillation. For example, if the ac line voltage rose a few volts, increasing the B plus supply and heater voltages, immediately the amplitude of the positive (and negative) grid signal swings would increase, the number of electrons striking the grid would increase, the grid leak bias would become more negative and the g_m and gain of the tube would decrease, bringing the amplitude of the oscillations close to their original value.

Most oscillators employed in tape recorders operate by applying positive feedback between appropriate tube elements, usually between plate and grid, in an amount sufficient to sustain oscillations in a tuned circuit consisting of a coil and capacitor. The values of the coil and capacitor essentially determine the frequency of oscillation.

The operation of a tuned-circuit oscillator is a complex process, with many things happening at the same time. A complete description requires tracing over one cycle of oscillation the phase relationships between voltage and current in electromagnetic and electrostatic fields and in a tube circuit. While space does not permit such a step-by-step analysis for the more common oscillator circuits, an attempt will be made to provide a basic insight into how they work.

A fundamental explanation can be based around Fig. 801,

which shows a simple oscillator, similar to that found in many moderate-price tape recorders. To help understand why oscillation takes place, it is helpful to consider just the tuned circuit, comprising C1 and L1. Assume that for some reason the upper plate of C1 is charged, that is, contains more electrons than the lower plate. Seeking equilibrium, electrons tend to flow from the upper to the lower plate through the path afforded by L1. This flow creates an electromagnetic field about the coil and, by Lenz's law, induces a voltage across the coil in a direction such as to prevent electrons from flowing rapidly through the coil. Thus the

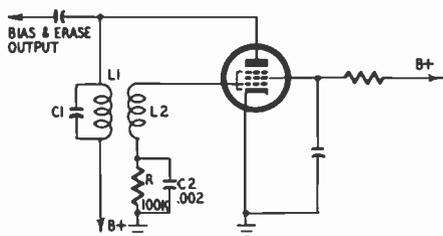


Fig. 801. Single-ended oscillator, employing plate-to-grid feedback.

electron flow gradually reaches a maximum and then starts to slow down as the charges on the upper and lower plates approach equilibrium. However, when the rate of discharge of electrons from the upper to the lower plate begins to slow down, the field of L1 begins to collapse. By Lenz's law, a voltage is again induced which opposes the change in electron flow through the coil. Thus the collapsing field promotes the continued flow of electrons from the upper to the lower plate. In this manner the lower plate collects not just enough electrons to restore equilibrium with respect to the upper plate (zero voltage across the capacitor); rather it accumulates an excess of electrons compared with the upper plate.

Eventually the coil's field has fully collapsed so that no more electrons arrive at the lower plate. Now this plate has an excess of electrons (in other words, the capacitor has an electrostatic field, which is the counterpart of the coil's electromagnetic field). Therefore, electrons begin to flow from the lower to the upper plate through the coil. As before, an electromagnetic field is built up around L1 and, when this field collapses, it results in the continued accumulation of electrons on the upper plate of C1 so that the original state of matters is restored: an excess of electrons on the upper plate. This completes one cycle of oscillation.

Assuming no resistance in the coil and no load, the tuned circuit produces a perfect sine wave, eminently desirable for tape recording purposes to achieve a minimum of noise. In practice, this is, of course, impossible; some distortion is always present.

The frequency of oscillation—or the time required for one cycle—essentially depends upon the values of L and C (to some extent it is also governed by the slight amounts of inductance and capacitance found in the tube and other components associated with the tuned circuit). The coil and capacitor values, *in conjunction with each other*, determine how long it takes for the electromagnetic field of L to build up and collapse and for the electrostatic field of C to build up and collapse. The larger the inductance of L , the longer its field takes to grow and fall. Similarly, the larger the capacitance, the longer it takes to discharge electrons from one plate to the other. At the oscillation frequency,

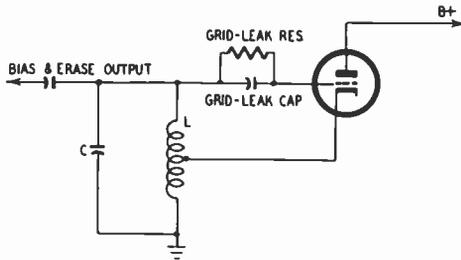


Fig. 802. *Single-ended oscillator employing cathode-to-grid feedback.*

the charge or discharge rates of the two components are equal and work in unison: the electromagnetic field stores energy for the same period that the capacitor is able to deliver it and then, in turn, the capacitor stores energy for the same period that the coil is able to deliver it.

Another way to appreciate why a circuit such as Fig. 801 oscillates at one particular frequency is to consider the impedance between the plate side of the tuned circuit and ground. (It should be recognized that the bottom of the tuned circuit is effectively at ground so far as ac is concerned because of the filter capacitor always associated with B plus.) Maximum impedance of the tuned circuit occurs at the frequency where the reactances of L and C are equal. For any other frequency, the impedance is less so that either the coil or capacitor tends to serve as a shunt to ground. Consequently, alternating current developed through oscillation tends to be shunted to ground except at the frequency where the impedance is maximum.

Once started, oscillation in a tuned circuit would theoretically continue forever were it not for various losses, including those due to resistance in the coil, leakage in the capacitor and the load presented by the tape recorder heads and other circuit elements. For oscillation to be sustained, the tuned circuit needs outside aid. This is similar to the case of the child on a swing, who keeps moving as the result of a moderate systematic push from someone on the ground.

The tuned circuit receives systematic aid from the tube circuit with which it is associated. When the upper plate of C1 is to be

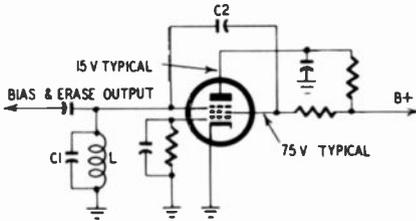


Fig. 803. Single-ended oscillator employing the transitron principle.

charged, matters are arranged (as indicated in the next paragraph) so that tube current increases, thereby sending more electrons to this plate. Conversely, when the lower plate of C1 is being charged, tube current decreases, sending more electrons to this plate (from the viewpoint of ac, a decrease in tube current is in effect a flow of electrons from B plus toward the tube).

The purpose of L2 in Fig. 801 is to vary the grid voltage in a manner which causes tube current to assist the oscillation process. The changing electromagnetic field of L1 cuts across L2 and, by transformer action, induces a voltage across L2—that is, between grid and ground. The windings of L2 are so connected to grid and ground that, when tube current is increasing, the grid end of L2 goes positive, which causes a further increase in tube current. This, of course, is positive feedback. Similarly, when tube current is decreasing, the grid goes negative, resulting in a further reduction in tube current.

The cumulative increase or decrease in tube current which takes place due to positive feedback approaches an end when the charge on either plate of C1 approaches maximum. There is a slowing collapse of the magnetic field around L1 and eventual reversal of this field as C1 approaches maximum charge and then begins to discharge. This results, through transformer action, in

a decrease in grid voltage (positive or negative as the case may be) and eventual reversal of its polarity.

Though belated, an explanation of how oscillation gets started is now appropriate. Assuming that B plus has been applied to the circuit and current supplied to the tube heater, initially there is zero voltage between grid and cathode. Due to the random motion of electrons emitted from the cathode, a minute voltage will appear at the grid. Assume that at a given instant this voltage is positive-going. Therefore the current through the tube increases. This increase in tube current results in a charge on C1, a change in the electromagnetic field of L1, positive feedback at the grid, a further increase in tube current—and the process of oscillation is on, as already described.

Although grid-leak bias keeps the amplitude of oscillations from being extremely high, it is very desirable that feedback be limited so that the tube operates within the linear portion of its characteristic in order to maintain an oscillation waveform with minimum harmonic distortion. In the case of Fig. 801, feedback is controlled by using a proper ratio of turns and the right amount of coupling between L1 and L2, thus limiting the voltage fed back to the grid. Ideally the tube operates class A, in the linear range of its characteristic, though occasionally the higher output capabilities of class B or class C operation are necessary, with attendant higher distortion. A more conservative choice of circuit or tube is not always economically feasible.

There are a number of variations of the single-ended oscillator of Fig. 801, most of which rely on positive feedback. In some instances the oscillator coil is in the grid-cathode circuit, as in Fig. 802. For positive feedback to occur here, it is necessary that the grid go positive relative to the cathode when tube current increases, and negative when current decreases. Positive grid-cathode voltage, in turn, increases tube current, and negative grid-cathode voltage decreases it. The cumulative buildup or decrease in tube current is controlled by the tuned circuit so as to sustain oscillation.

Assume that the current flowing from ground through the lower part of oscillator coil L and then through the tube is momentarily increasing. This increasing current induces a voltage across the grid-ground portion of the coil such as to oppose the increase. That is, the inductive reactance of the coil causes a voltage drop across it, causing the cathode end to go positive with respect to the ground end. By autotransformer action, the positive-going voltage at the cathode appears as a still more positive

voltage at the grid, causing a further increase in tube current. Thus, as in the case of Fig. 801, positive feedback is present. The voltage between grid and ground causes the capacitor C to charge, makes the grid end positive and the ground end negative. Since the tube current cannot increase without limit, the tube current eventually reaches a maximum, that is, a steady value. As a result there is no longer an induced voltage due to *tube* current increasing. Consequently the grid to ground voltage decreases and capacitor C discharges upward through the coil.

As the grid to ground voltage decreases, the grid to cathode voltage decreases and the tube current decreases also. This induces a voltage in the lower portion of the coil, this time negative at the top and positive at the ground end. As before, autotransformer action causes the grid to go more negative with respect to the cathode, further reducing tube current, making the grid still more negative, and thus assisting the upper plate of the capacitor to go negative with respect to the lower plate. It should be kept in mind that the process of positive feedback and the turning points from increasing to decreasing tube current are under control of the tuned circuit, which determines the rate of increase and decrease in tube current and thus the frequency of oscillation. Finally, it may be pointed out that while the locations of the grid-leak resistor and capacitor are different in Fig. 802 than in Fig. 801, the action is exactly the same.

The self regulation of the grid-leak bias system is not perfect, of course, but is sufficient to make the oscillator relatively insensitive to line voltage variations, changes due to normal heating of the components, and tube aging.

The grid capacitor loses some of its charge during every cycle but unless the oscillations are getting smaller, each positive grid swing will recharge the capacitor, thus maintaining the bias voltage. The time constant of the grid-leak capacitor and grid resistor (product of R times C) determines how long the capacitor can discharge through the resistor before the voltage has dropped appreciably. It should be roughly 5 to 10 times the period of one cycle of oscillation to maintain grid bias adequately. For example, if the oscillator frequency is 50,000 cycles per second, one cycle is $1/50,000$ second, or 20 microseconds (μsec); 10 times this amount is 200 μsec . The time constant of the 100,000-ohm resistor and 0.002- μf capacitor in Fig. 801 is 200 μsec .

Occasionally encountered in tape recorders is the "transitron" circuit, which does not depend upon positive feedback, as the majority of oscillators do. This is illustrated in Fig. 803. Its opera-

L2 and the grid instead of between the bottom of L2 and ground, as in Fig. 801. The grid-leak action is the same in either case.

Push-pull oscillators

The great majority of professional tape recorders and a fair number of moderate-price ones employ a push-pull oscillator, using two triodes or, customarily, two halves of a dual triode. While one triode is in the positive half of its oscillation cycle, the other is in the negative half. Thus, symmetrical forces are at work, tending to reduce even-harmonic distortion.

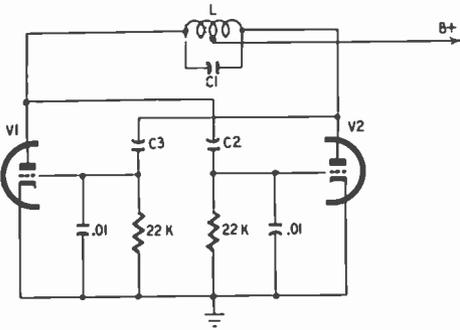


Fig. 805. Typical push-pull oscillator. Oscillator frequency typically 30,000 cps.

Distortion in the bias waveform is a source of noise. Moreover, the greater the demands upon the oscillator to provide enough current for adequate erasure, the greater is the likelihood of distortion. Because of its lower distortion for the same output, the push-pull oscillator is favored in professional machines.

Fig. 805 shows a typical oscillator of this kind. Feedback is from the plate of V1 to the grid of V2 through capacitor C2; and from the plate of V2 to the grid of V1 through capacitor C3. C1, as well as C2 and C3, together with coil L, essentially determine the resonant frequency.

Assume the grid of V1 is positive-going at a given instant. This produces a negative-going voltage at the plate of V1, which is transferred to the grid of V2, causing the plate of V2 to go positive. The voltage fed from the plate of V2 to the grid of V1 is therefore of the same polarity as the original signal on this grid; feedback is positive. The same is true for the voltage fed from the plate of V1 to the grid of V2. However, the voltages on the grids of V1 and V2 are of opposite polarity so that one triode is

in the positive half-cycle while the other is in the negative half. B plus is supplied to the plates of V1 and V2 through the center-tapped coil L. The grid resistors and grid capacitors of each triode produce a negative dc bias in the same manner as explained in connection with Fig. 801.

The feedback capacitor of each triode forms a voltage divider in conjunction with the grid capacitor. Voltage-divider action limits the amount of feedback to the grid, preventing the tubes from being driven excessively. In Fig. 805, the $0.01\ \mu\text{f}$ grid capacitor has a reactance much smaller than 22,000 ohms at the bias frequency, roughly 50,000 cycles, so that the voltage divider consists principally of the feedback and grid capacitors.

There are a number of variations of this basic push-pull circuit. One with several features of interest appears in Fig. 806. There is no separate resonating capacitor such as C1 in Fig. 805.

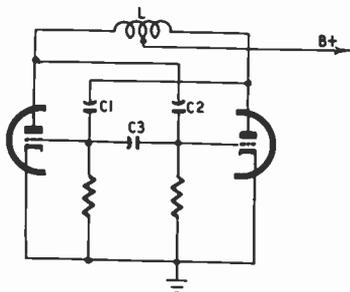


Fig. 806. Variation of the push-pull oscillator. C3 is appreciably larger than C1 and C2.

Instead, the resonant frequency is determined by L and the feedback capacitors C1 and C2, which are linked by the relatively small reactance of C3. C1 and C2 are thus effectively in series with each other and in parallel with the oscillator coil. It will be noted that separate grid-leak capacitors do not appear in Fig. 806. Instead, capacitors C1 and C2 perform an additional task, acting to maintain negative bias at each grid. The voltages appearing at the grid ends of C1 and C2 vary between zero and some negative value. The grid voltage cannot go above zero because the resultant grid current charges the grid capacitors negatively at the grid side. Thus a negative charge is built up on the grid side of each capacitor.

Often, to supplement the dc bias obtained by grid-leak action, cathode bias is also used. That is, instead of connecting the cathodes of the triodes directly to ground, they are both connected to ground through a common resistor with a value of several hundred or a few thousand ohms.

Coupling the oscillator to the heads

To couple the oscillator effectively to the record and erase heads, it is necessary to consider the requirements of the oscillator as well as the heads.

The voltage across the oscillator coil varies directly with the Q of the resonant circuit. Without a load, the Q of the parallel inductance and capacitance depends almost entirely upon the ratio of the coil's reactance to its resistance at resonance. The Q is reduced by any load presented to the oscillator; say by the heads. The greater the loading (the smaller the resistance in parallel with the tuned circuit), the smaller is the Q , therefore reducing oscillator output voltage and very likely increasing the distortion. Moreover, the lower the Q , the less exact is the frequency of oscillation. Thus slight changes in the gain of the tube or in B

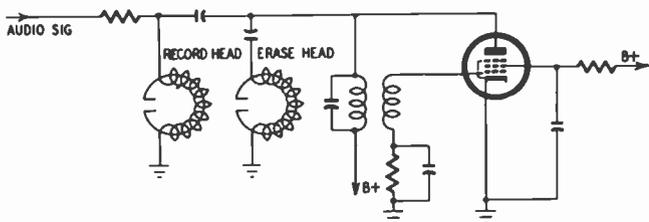


Fig. 807. Direct coupling of the oscillator to record and erase heads.

plus voltage can have an appreciable effect upon frequency. Coupling circuits, such as a small capacitor, are often affected by frequency and a shift in frequency of oscillation accordingly impairs performance.

From the viewpoint of the heads, the oscillator must provide sufficient voltage to cause the required current to flow through them. The voltage directly available at the oscillator, say at the plate in the case of a single-ended oscillator such as in Fig. 801, may be sufficient to drive the heads, or it may be too much or too little. Where the voltage is insufficient, transformer coupling is often used; a winding on the oscillator coil steps up the available voltage to the required amount.

As a result of the dual need to avoid undue loading of the oscillator and at the same time supply proper current to the heads, one finds many variations in coupling. Moreover, because of the different requirements of the record and erase heads, one often finds the oscillator current coupled to the record head in one fashion and to the erase head in another.

Considering single-ended oscillators first, Fig. 807 illustrates the use of direct coupling to both the record and erase heads. The value of the coupling capacitor and the inductance of the head determine the amount of current flowing through each head. A resistor is used to prevent the audio source from adversely affecting the oscillator circuit. The typical "constant current" resistor described in Chapter 4 serves admirably. Because of its high reactance even at the highest audio frequencies, the bias coupling capacitor prevents the oscillator coil from shunting the audio current around the record head.

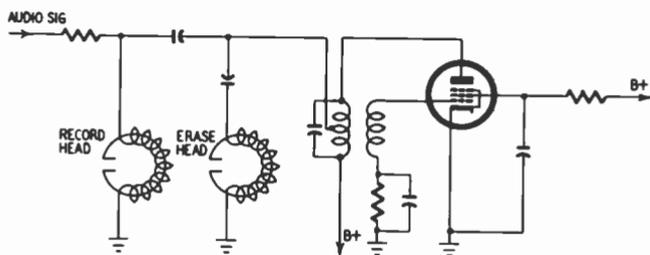


Fig. 808. *Alternate method of direct coupling to reduce loading effect upon the oscillator.*

Fig. 808 is a variation of Fig. 807, the only difference being that oscillator voltage is taken from a tap on the primary of the coil instead of at the top of the coil (plate of the tube). The reason for doing so is to reduce the loading effect of the heads upon the oscillator. Obviously, if the connection were made at the bottom of the coil, there would be no loading whatsoever (and no voltage to the heads), whereas the top connection represents maximum loading (and maximum voltage). An intermediate position reduces loading and at the same time permits adequate voltage to be applied to the heads. The primary of the oscillator coil is designed with the tap properly located to apply the required voltage to the heads.

A quite popular method of coupling a single-ended oscillator to the heads is illustrated in Fig. 809. Here a tertiary winding is employed which serves both to isolate the heads from the oscillator coil and at the same time provide them with the required voltages.

In the case of push-pull oscillators, the record head is seldom directly coupled to the oscillator coil, although there are exceptions. Record heads are ordinarily unbalanced, one end of the winding being connected to ground. Direct coupling would load

down one triode and not the other, impairing the all-important symmetry of the oscillator. Therefore, as a rule, a secondary winding is used for coupling the oscillator current to the record head (Fig. 810). The secondary also supplies current to the erase head.

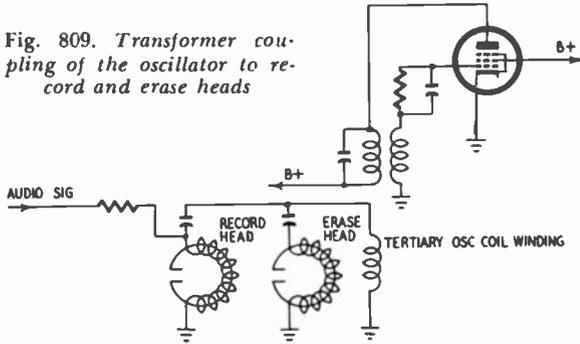


Fig. 809. Transformer coupling of the oscillator to record and erase heads

Because of the relatively high impedance of the erase head at the bias frequency, a substantial voltage must be generated by the oscillator to drive sufficient current through the head. However, the required voltage can be reduced by utilizing a series-resonant circuit, as shown in Fig. 810. If the capacitor and head inductances resonate at the oscillator frequency, the series im-

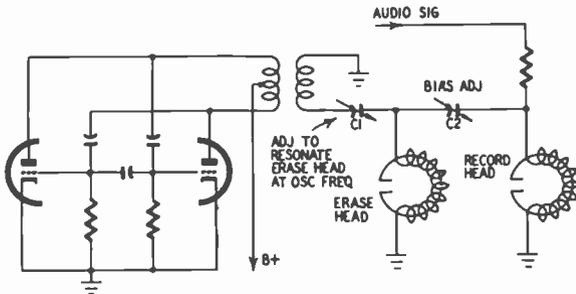


Fig. 810. Transformer coupling of the push-pull oscillator to unbalanced heads.

pedance of these components is at a minimum and a relatively low voltage will cause adequate current to flow throughout the erase head. The same principle can be employed for single-ended oscillators (Fig. 809) where the capacitor in series with the erase head can be selected to resonate with the head at the bias frequency.

Returning to Fig. 810, let us consider the needs of the record head with respect to bias current. Current demands are much smaller for bias than for erase, and at the same time the imped-

ance of the record head is generally greater than that of the erase head, so a substantial driving voltage is still necessary for the record head. It may be, therefore, that the voltage across the secondary of the oscillator coil is insufficient to meet the bias current needs of the record head. This high voltage can be obtained across the erase head itself (Fig. 810). Although the voltage across the head and capacitor in series is low, that across the head alone is much higher (voltage equals reactance times current).

Whereas the erase head in Fig. 810 is shown connected to ground, it is feasible to couple it directly to the plates of the oscillator triodes, as illustrated in Fig. 811. Voltage for the record head, however, is still taken from a secondary winding on the oscillator coil.

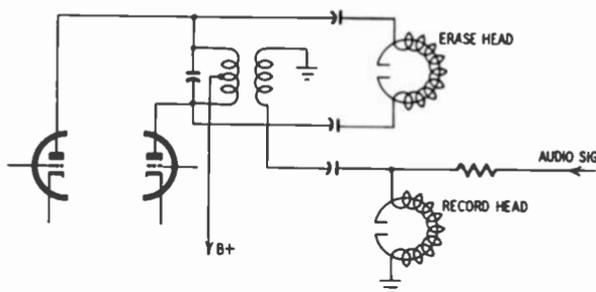


Fig. 811. Direct coupling of the push-pull oscillator to the erase head.

It may be questioned why coupling capacitors are used for the balanced line connection to the erase head in Fig. 811. Apparently, since the triode plates are theoretically at the same B-plus voltage and the primary has practically no dc resistance, there is no dc across the primary coil. Such dc would produce modulation noise on the tape as well as magnetize the head, thereby producing further noise. However, any unbalance in the oscillator *would* cause dc to flow through the erase head so that the coupling capacitors, although theoretically unnecessary, do offer a practical safeguard.

Fig. 812 presents one of the rather rare instances in which direct coupling is used with a push-pull oscillator for both the record and erase heads. For the erase head, direct coupling presents no symmetrical loading problem because this head is not connected to ground. In the case of the record head, however, which is of the usual unbalanced type, direct coupling does tend to upset the symmetry of the oscillator by loading V1 and reducing its output.

However, resistor R compensates by loading V2, so that the output of V2 is reduced more or less to the same extent as V1.

Fig. 813 is somewhat similar to Fig. 812 but here the circuit is

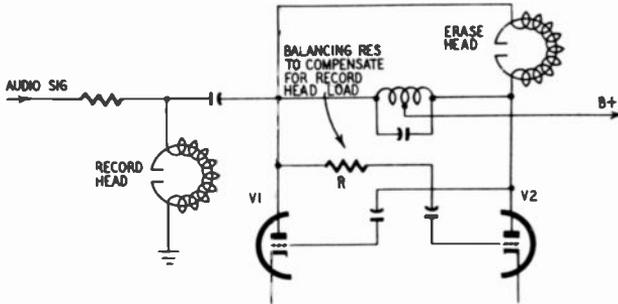


Fig. 812. Direct coupling of the push-pull oscillator to both heads.

further simplified by having the erase head act as the oscillator coil. The head has two windings whose junction serves as the center tap. Since the dc plate currents flow through the erase head in opposite directions, theoretically no net dc should flow

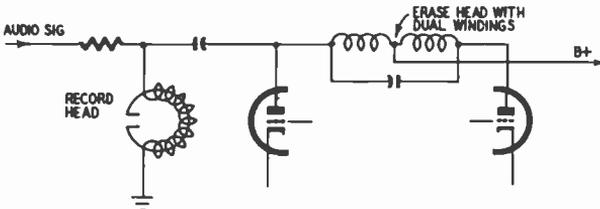


Fig. 813. Use of the erase head as the coil in a push-pull oscillator.

through the head. Bias current for the record head is taken from one of the triode plates but in this case no attempt is made to compensate for the resulting unbalance in the circuit. The record head of this particular machine has quite a high impedance. Its loading effect is therefore rather small and the amount of unbalance caused in the oscillator is slight enough so that quality of performance is consistent with that which can reasonably be expected of a tape recorder in its price class.

Most commonly, bias current is supplied straight to the record head, along with the audio signal, as shown in Figs. 807, 808, 809, etc. In a few instances, because of the type of oscillator tube and circuit used, not enough high-frequency voltage is developed to meet the needs of the record head. Therefore the bias is mixed

with the audio signal prior to the stage that drives the record head (Fig. 814). This stage provides the necessary amplification.

Control of bias current

The exact amount of high frequency current going through the erase head is not too important as long as there is enough to saturate the head without heating it to excess. Once the head is saturated, it is doing as good a job as its size and design permit. Further increases in current produce no significant improvements in erasure. The amount of bias current supplied to the record head is an altogether different matter. As indicated in the early part of this chapter, bias affects distortion and frequency response. Slight changes in bias produce relatively large variations in distortion and in treble response.

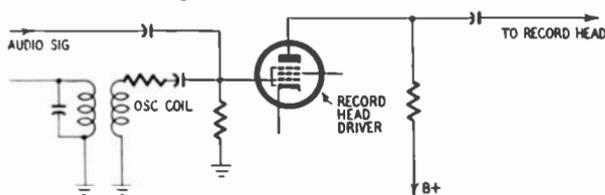


Fig. 814. *Mixing of the audio signal and bias current prior to the record-head driver.*

The optimum amount of bias current is that which reduces distortion to the fullest extent compatible with adequate high-frequency response and a satisfactory signal-to-noise ratio. Optimum bias current, particularly at tape speeds below 15 ips, varies with the manufacturer's or user's concept of an acceptable limit to high-frequency response. At 7.5 ips, some may consider nothing less than response flat to 15,000 cycles as acceptable while others, in exchange for lower distortion and/or higher signal-to-noise ratio, may be willing to settle for a fairly flat response to 12,000 or even 10,000 cycles. Thus, the decision as to the optimum combination of high-frequency response, distortion and signal-to-noise ratio determines the specific amount of bias current desired. It should be taken into account, furthermore, that this specific value varies somewhat from one brand of tape to another and from one kind of tape to another (regular versus high output).

In view of the critical nature of the amount of bias used, together with the fact that the optimum value varies among tapes, it is highly desirable, where the utmost in recording quality is

sought, to provide some means for varying bias current. This the professional tape recorders do almost without exception. A few of the moderate-price ones do also. Sometimes the bias control is intended only for factory adjustment and is mounted fairly inaccessibly inside the tape amplifier. In other instances it is made readily available either at the rear panel of the amplifier, above chassis or even on the front panel. On the other hand, some mechanical safeguard has to be provided against accidental disturbance of the optimum setting; for example, the control shaft may be recessed behind a hole and require a screwdriver for adjustment.

One method of varying bias current is to place a variable resistor between the bias supply and the record head. The disad-

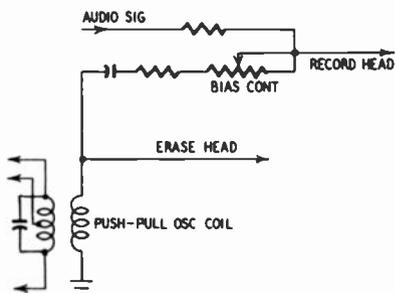


Fig. 815. Control of bias by a variable resistance.

vantages of a potentiometer, however, are that it is apt to become noisy in time and dissipates power because of current passing through a resistance. This consumption of power places an extra burden on an already hard-working oscillator.

Use of a variable series capacitor instead of a resistor has the advantage of not absorbing power. But there are drawbacks, too. The variable capacitor is usually of the mica compression type, with air and mica serving as the dielectric. Its open construction makes it vulnerable to heat, humidity and dust, all of which tend to cause changes in capacitance after the optimum setting has been determined. Furthermore, a series capacitor discriminates more against the fundamental of the bias frequency than against its harmonics so that the effective harmonic distortion of the bias frequency is increased, resulting in greater recorded noise than if the fundamental and harmonics were passed to the same extent. (Although a variable inductor could be used instead to discriminate against harmonics, the extra expense and shielding problems of a coil generally militate against this expedient.)

While the proper choice of bias current control depends upon the particular circuit employed, on the whole the most satisfactory method is provided by the series potentiometer. Its range of control should be limited by making the potentiometer only part of the total series resistance, as illustrated in Fig. 815. This has two advantages (1) It prevents supplying an excessive amount of high-frequency current to the record head, possibly resulting in injury to the head through overheating. (2) Since the potentiometer controls only a portion of the total resistance, the amount of adjustment per degree of rotation is small, permitting very precise settings to be obtained easily. Depending upon the amount of current handled, it may be necessary to use a wirewound unit because of the larger wattage ratings in which the latter are available; but in many cases the less-expensive carbon potentiometer suffices.

To facilitate proper control of bias current, most tape recorders that incorporate a meter for indicating record level also use this meter, through a suitable switch, for measuring bias. Since bias requirements vary somewhat from one brand or kind of tape to another, the experienced user gets to know the proper setting for each tape that he uses. Due to tube and component aging, the output of the oscillator usually tends to drop over a period of time. This decrease may result in gradual deterioration of quality in the recorded tape. The meter immediately notifies the operator of a decline or possible increase in bias. The usual technique of metering bias current is to measure the voltage across a small series resistor between the record head and ground. Erase head current can be similarly metered, although this is seldom done because erase-head current can change over a fairly substantial range without affecting performance.

Drift

As the oscillator warms up, its output tends to change slightly. The period of drift may last from 15 minutes to $\frac{1}{2}$ hour or more. Professional users allow a liberal amount of warmup time before putting their tape recorders to work to permit the oscillator (as well as other elements of the machine, including the transport) to stabilize.

Bias current flowing through the record head can vary because of changes in oscillator frequency. These frequency changes may alter the output of the oscillator and/or they may affect the coupling between head and oscillator. Furthermore, output of

the oscillator may be affected by changes in the value of the load.

Generally, the factors primarily responsible for the change in oscillator frequency are the resonant coil and capacitor. The coil has an inherent positive temperature coefficient; that is, its inductance rises with temperature, reducing the oscillator frequency. The ordinary capacitor also has a positive coefficient, which further reduces the resonant frequency. But capacitors with negative temperature coefficients are available so that a close approach to a stable circuit can be had by using them in the tuned circuit.

Changes in resonant frequency affect the Q of the tuned circuit slightly by altering the coil's ratio of inductive reactance to resistance at the resonant frequency. Increased Q results in greater voltage output by the oscillator tube while reduced Q decreases output.

Other factors responsible to a degree for drift in oscillator output are temperature effects upon vacuum tubes, upon components which constitute the load on the oscillator, and upon plate voltage variations. Temperature changes cause the spacing between tube elements to vary, thereby altering interelectrode capacitances and transconductance. Changes in value of load components, due to temperature, affect the Q of the resonant circuit, which in turn governs oscillator output in the manner already described. Variations in plate voltage on the oscillator tube successively affect resonant frequency, Q , and output.

Frequency stability depends substantially upon how sharply the resonant circuit is tuned, which is a function of its Q . A heavy load makes for a broadly rather than sharply tuned circuit and therefore causes the oscillator to be particularly susceptible to frequency drift, which can affect the coupling to the record head.

Apart from the effect upon output, variations in oscillator frequency can change the amount of bias current flowing through the head if a coupling capacitor is used between the oscillator and the head, as is generally the case. Reactance of this capacitor varies with frequency, therefore reducing or increasing bias current flow.

Although the foregoing discussion may cause the oscillator to appear oversusceptible to drift, this is not true for the usual manner in which it is operated in tape recorders. The oscillator, whether single-ended or push-pull, is generally operated with grid leak bias, where the grid voltage goes sufficiently positive on one half of the cycle for the grid to draw current. As already explained,

this current develops a negative bias on the grid by means of a grid-leak circuit. The amount of bias varies in a way that makes the circuit substantially self-regulating with respect to output voltage. If for some reason, say a slight drop in B-plus voltage, the oscillator output were to decrease, smaller feedback voltages would appear at the grid, and the grid capacitor would be charged to a lesser extent, resulting in lower grid bias. But a reduction in grid bias increases the transconductance of the tube, increasing the output. This, then, makes for a self-regulating circuit, tending to produce relatively constant voltage, independent of such factors as heater voltage, B-plus supply voltage, tube aging, load on the oscillator, etc.—within reason.

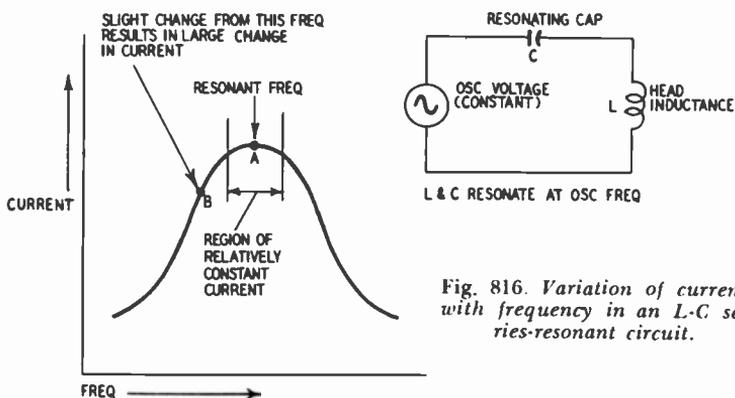


Fig. 816. Variation of current with frequency in an L-C series-resonant circuit.

By operating the oscillator with self bias and employing such measures as a negative coefficient capacitor in the resonant circuit, oscillator output and therefore bias current can be made relatively stable. A further means of limiting bias current drift to a minimum is to resonate the record head with a series capacitor at the oscillator frequency. In an L-C series resonant circuit, current depends upon frequency in the manner of Fig. 816. Current varies sharply with slight changes in frequency, except in the peak region, where there is somewhat of a plateau. Thus, if the oscillator frequency drifts slightly in the region of resonance (point A), the effect upon bias current is insignificant whereas, if it drifts in a region well-removed from resonance (point B), the effect upon bias current is pronounced.

Waveform

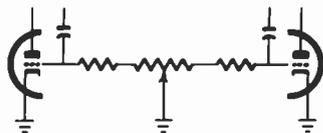
Optimum performance requires that the oscillator produce a perfect sine wave. Odd- and even-harmonic distortion components,

inevitably present to some degree, cause noise to appear on the tape. The principal offender appears to be second harmonic distortion.

For low harmonic-distortion content, it is necessary that the tuned circuit have a high Q . The action of the tuned circuit may be likened to that of a flywheel, converting periodic bursts of current from the oscillator tube (or tubes in the case of push-pull) into a steady sinusoidal current. In fact, this property of the $L-C$ circuit is often called the "flywheel effect." The higher the Q , the purer the waveform. A Q of about 10 is considered sufficient for providing fairly distortion-free current.

The Q is affected by the load on the oscillator. The load on the oscillator consists partly of current drawn by the heads and partly of current drawn by the grid on positive pulses. Excessive grid

Fig. 817. Use of a balancing control in a push-pull oscillator to reduce noise.



current, caused by either too much feedback or too low a value of grid-leak resistor, reduces the Q and in turn causes distortion to rise.

The push-pull oscillator can theoretically effect complete cancellation of second- and other even-harmonic distortion. Cancellation depends upon the degree of balance between the two halves of the oscillator circuit. Perfect balance requires that the transconductances of the two triodes be equal, that the tuned oscillator coil have an accurate electrical center tap, that the grid resistors and the feedback capacitors be matched. By using a dual triode such as the 12AU7 or 12BH7 the requirement of matched tubes can be satisfactorily met. Components with 5% tolerances meet the resistor and capacitor requirements adequately.

To insure symmetry between the two halves of a push-pull circuit, means are sometimes provided for balancing the triodes (Fig. 817). The grid resistors are connected to the outer terminals of a potentiometer, with the arm to ground. By adjusting the arm, the grid resistance of each tube is changed, which alters the grid bias and therefore the transconductance of the tube. If the tape recorder has separate record and playback heads, balancing can be done by ear; that is, by adjusting the control for minimum noise as heard in playback, without any audio signal fed into the recorder. Distortion can also be checked by using a bridged-T filter

to remove the fundamental, leaving the harmonics to be measured. Harmonic content of 1% or more can be a serious source of noise.

A series capacitor can be used to resonate the record head and thereby stabilize the amount of bias current flowing through it. Another advantage of this scheme is that of discriminating against harmonics of the bias current. Bias current through the head is maximum in the region of the fundamental oscillator frequency. At the second and higher harmonics, therefore, considerably less current reaches the head.

Although all the precautions indicated may have been taken, there can still be excessive harmonic distortion, particularly second-harmonic, for absolutely top-notch recording requirements as in a professional studio. Therefore, a filter is sometimes installed to suppress the second harmonic specifically.

Fig. 818 is an example of a trap designed to shunt the second harmonic of the oscillator frequency to ground. L1 and C1 are tuned to the second harmonic. R controls the amount of bias current. As shown by curve 1, the inductance of the head produces a 6-db-per-octave rolloff in bias current. L1-C1 puts a deep notch in this characteristic at the second harmonic, as shown by curve 2. As for higher harmonics, three factors account for only minute quantities of these flowing through the record head: (1) the inductance of the head causes a 6-db-per-octave rolloff with increasing frequency; (2) the level of the higher harmonics is initially weaker than that of the second harmonic; (3) reactance of stray capacitance decreases with rising frequency, eventually shunting the upper harmonics around the head.

The purpose of C2 in Fig. 818, a relatively small capacitor, is to prevent the audio signal to the record head from being shunted to ground through R and the oscillator coil.

Frequency

To prevent perceptible beats between the bias current and harmonics of the audio signal, the oscillator frequency should preferably be at least five times the highest recorded audio frequency. But this conflicts with what is best for the erase head. Since it is common practice to employ one oscillator to supply high-frequency current to both the erase and record heads, the oscillator frequency is often reduced by way of compromise. Thus, it is commonly found in recorders of good quality, which provide response out to 15,000 cycles or so at 7.5 ips, that the bias frequency is closer to 50,000 cycles than the preferable 75,000. On

the other hand, in a number of top-quality recorders no such compromise is made and the frequency is kept upward of 75,000 cycles.

To drive the required amount of current through the erase head, a relatively high voltage is needed because the head has considerable reactance at the oscillator frequency. Were the frequency lower, the reactance of the head would be smaller and the voltage demand upon the oscillator would be less. On the other hand, there is the conflicting requirement that the erase head must put each particle on the tape through several complete magnetic cycles while the particle is within range of the head's magnetic field. Therefore too low an oscillator frequency is not desirable.

In summary, the erase head is best served by a frequency high

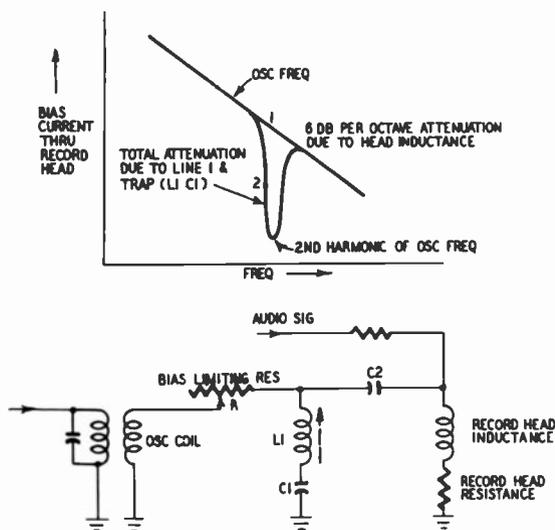


Fig. 818. Use of an L-C trap to reduce second-harmonic distortion in the bias waveform.

enough for effective erasure yet low enough to make modest voltage demands on the oscillator.

In a few recorders, particularly of earlier years, the requirements of the erase and record heads are individually satisfied by employing separate oscillators, thus making different frequencies as well as amounts of current readily available. In at least one unit, although only one oscillator was used, different frequencies were obtained by supplying current at the fundamental frequency to the erase head and using the third harmonic for bias current.

A transformer, with the primary connected between the cathode of the oscillator and ground, was tuned to the third harmonic. This signal was then amplified and fed to the record head.

Stray pickup

If the oscillator frequency finds its way into the record-level circuit, it will give a false upward indication of record level, resulting in an underrecorded tape and a reduced signal-to-noise ratio. If it finds its way into the record amplifier, it may be amplified along with the audio signal and, perhaps in accordance with the volume control setting, increase or decrease the amount of bias reaching the record head. It may cause other undesirable effects, such as oscillation or blocking of amplifier stages.

The oscillator frequency may find its way into unwanted places through stray capacitance or radiation. The higher the frequency, the greater the extent to which it exhibits radio-frequency characteristics. Therefore, the oscillator coil, the chief source of radiation, must be properly shielded and located as far as possible from circuits where stray pickup may do harm. In some tape recorders a toroidal (doughnut-shaped) oscillator coil is used which theoretically has no external magnetic field. However, toroidal coils are expensive.

To prevent stray pickup of bias voltage, care must be taken with respect to the location and lead dress of vulnerable circuits. Through radiation, the oscillator frequency may be picked up by open switch terminals not used in the record mode. Unless grounded or otherwise properly terminated, these open terminals serve as antennas for stray pickup.

record-level indicators

THE tape recordist may record at a level so high as to produce excessive distortion. Or, to avoid distortion, he may record at a level so low as to result in a poor signal-to-noise ratio. Given a good tape recorder, he can chart his way between these extremes with a fair but by no means lavish margin of safety.

The recordist steers his course by means of the record-level indicator. His success depends not only upon the type and quality of indicator used, but also upon the manner in which the indicator is connected to the record amplifier circuit, upon its calibration, upon avoiding the pickup of extraneous signals and upon his skill in interpreting what he sees.

While the principal function of the indicator is to guide in setting record level, two other important functions are usually performed if the indicator is of the meter type: metering playback level, and bias (and sometimes erase) current.

Types of indicators

Record-level indicators can be sorted into mechanical and electronic types. Mechanical indicators employ a dc microampere or milliamperere movement, the audio signal being converted to dc by a rectifier. Electronic indicators consist of either an electron-ray (magic-eye) tube or neon lamp, which may be driven directly by the audio signal or, in the case of the electron-ray tube, by a rectified voltage.

The principal type of mechanical indicator is the VU meter,

very widely employed in professional audio work. However, not every meter equipped with a VU scale is a true VU meter, which must possess several specific characteristics. Although an operator can, with practice, acquire the knack of properly interpreting any meter, the VU meter has the advantage of standardization; it is a familiar item to those in professional work and therefore its readings have a recognized meaning.

At one time the volume indicator, sometimes referred to as a recording-level meter or decibel meter, enjoyed popularity, but is now in limited use. This and the VU meter have relatively high sensitivity and, since they contain their own rectifiers, may be driven directly by a moderate signal of less than 2 volts. Another variety of mechanical indicator employs a less sensitive dc meter

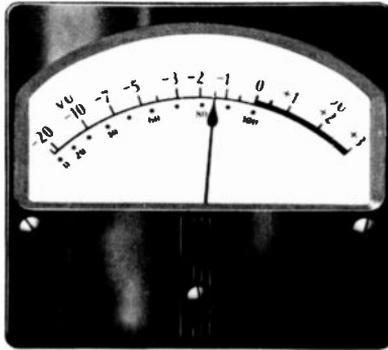


Fig. 901. Volume-unit (VU) meter showing A scale.

and needs external amplification before rectification of the ac signal; this type may be referred to as a vacuum-tube voltmeter (vtvm). The foregoing all read average signal level. Still another vtvm type is designed to read peak level.

In the realm of electronic indicators, the neon lamp is most popular because it is least expensive. However, it does not provide as much information as the electron-ray tube and requires a good deal more audio signal to drive it.

The VU meter

The VU meter (Figs. 901 and 902) contains a 50-microampere dc movement with a full-wave copper oxide rectifier. The standard meter has a 4-inch dial with a double scale. One scale reads from -20 to +3 VU. The other reads from 0 to 100 (percent); 100 coincides with 0 on the VU scale. The photos show these scales on

internal resistor) of 3,900 ohms. Thus the total load across the 600-ohm line is 7,500 ohms.

The standard VU meter must possess certain dynamic characteristics when connected across a 600-ohm line, mentioned above. The sudden introduction in the line of a sine wave with a power of 2.5 mw should produce an overshoot between 1 and 1.5%. The pointer should be able to reach 99 on the 0-to-100 scale within 0.3 second. The frequency response must deviate by no more than ± 0.5 db between 25 and 16,000 cycles, referred to 1,000 cycles as 0 db. Between 35 and 16,000 cycles this deviation should not exceed ± 0.2 db. Distortion produced by placing the VU meter across a 600-ohm line should not exceed 0.3% harmonic. The meter must be able to withstand for $\frac{1}{2}$ second a voltage 10 times that required to produce a 0 VU reading. It must be able to withstand continuously a fivefold voltage overload.

In professional work—recording, broadcast and motion picture studios—the VU meter is generally used (in series with a 3,600-ohm resistor) across a 600-ohm line. The maximum signal level in such lines is commonly designed to be 4 db above 1 mw, which causes the meter to read 0. However, in some instances the maximum level is 8 dbm, and in this case an appropriate attenuator is placed ahead of the VU meter to cause it to read zero at an 8 dbm level.

As a record-level indicator and as a means of measuring bias and erase current, it is of little or no importance what the VU meter means in terms of power in a 600-ohm line. This is of importance only in measuring playback level. For measuring record level, what is important is that a given point on the scale, usually 0 VU, correspond to the level producing maximum permissible distortion on the tape. For measuring bias or erase current, a given point on the meter, usually 0 VU, should correspond to the correct amount of current. If the VU meter is so connected that it is in series with a 3,600-ohm resistor across a 600-ohm line when measuring record level, then the desirable dynamic characteristics of this instrument will be retained. When measuring bias or erase currents, which are steady, the dynamic characteristics are of no consequence and the meter can be used in any convenient manner.

(These considerations also pertain to meters other than the VU meter and need not be discussed further.)

The VU meter indicates average signal level, and allowance must therefore be made for peaks.

The very high sensitivity of the VU meter is obtained by means

of a special magnetic alloy with a large flux. Mounting the meter on a steel panel tends to shunt some of this magnetic flux, upsetting the meter's calibration. Therefore VU meters intended for such mounting must be specially calibrated by the manufacturer upon the basis of panel thickness.

The volume indicator

Unlike the VU meter, this once-popular indicator is not standardized. Also, it has less sensitivity, requiring more than twice as much drive voltage. It is generally driven to a full-scale reading

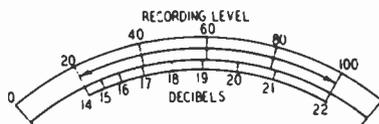


Fig. 904. Scale of a typical volume indicator.

by 6 mw of power in a 500-ohm line. Speed of response, amount of overshoot, frequency range and distortion produced by placing the meter directly across an audio line vary according to brand and model. Moreover, the dial conforms to no standard. A representative dial is shown in Fig. 904, featuring a 0-to-100 scale and also containing a scale reading from 14 to 22 db. As in the VU meter, the volume indicator reads average level so allowance must be made for peaks.

Vtvm type indicator

The vtvm type indicator that reads average signal level generally uses a 1-ma movement, which does not necessarily incorporate the standardized speed, overshoot limits and other characteristics of the VU meter, although it may have a VU scale. A vacuum-tube amplifier supplies the current which is required after rectification to drive the meter.

Indication of peak rather than average signal level may be had by means of a circuit described later. Although this eliminates the necessity of making an allowance for the margin between average and peak signals, several reasons account for the limited use of this type of indicator, at least in the United States. One is simply that the professional operator has grown accustomed to reading a meter that shows average level and makes his judgments accordingly. The practiced operator, using a VU meter,

can come within 1 db of the gain settings obtained by reference to a peak-reading instrument. Very often the operator is interested only in keeping distortion down over the average level and is quite willing to accept relatively large amounts of distortion on the short duration and comparatively infrequent peaks. Moreover, the peak-reading meter is less than perfectly accurate in its indication of peak level because some transients are not of sufficient duration to drive it to full indication.

The electron-ray tube

Fig. 905 illustrates the action of an electron-ray tube, the most popular type being the 6E5. When record level is sufficient to cause excessive distortion, the shadow of the eye is closed or nearly so. When the record level is too low for a satisfactory signal-to-noise ratio, the shadow is wide open. Thus the recordist seeks that gain control setting which barely keeps the eye open. However, transients (rapid changes in signal level) are difficult to follow, and to make life easier for the recordist some tape machines incorporate a "floating action" which for a brief while keeps the eye near the peak levels reached.

The neon lamp

The neon-lamp indicator, almost always an NE-51, lights when the record level is high enough to cause undue distortion. However, it does not warn the recordist when the record level is too low. Therefore, some recorders employ two neon lights. One, labeled "normal" (or some similar term) is calibrated to light so long as the record level is adequate for a satisfactory signal-to-noise ratio, while the other, labeled "distort," ignites when the record signal reaches a level producing excessive distortion. The recordist tries to set gain so that the normal light is on most of the time and the distort light is on seldom or never.

Mechanical vs. electronic indicators

Although more costly, mechanical indicators have an important advantage over electronic ones in that they inform the practiced operator in terms of decibels or percentage how much the record level is above or below the level producing maximum permissible distortion. Neon lamps only indicate when the level is too high or too low, but not by how much. The same is largely true for the electron-ray tube; while there is a variation from full shadow

to no shadow, the range is not calibrated and its meaning is uncertain.

A recordist may decide, for example, to set the record level 6 db lower than usual for a given type of music because past experience tells him that this is necessary to avoid excessive distortion due to unusually large peaks or because the type of music is such that distortion would be noticeable. He can reduce record level close to 6 db with the aid of a meter but not with the aid of an electronic indicator.

An advantage of the meter, particularly the VU meter, is that it is a relatively uniform product. In a given circuit, various meters of the same kind can be substituted and will produce essentially the same reading. In the case of electron-ray tubes and neon lamps, manufacturing tolerances are large enough so that individual tubes or lamps of the same type can produce significantly different readings in a given circuit.

Still another advantage of the meter type of indicator is that it

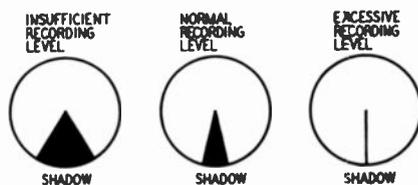


Fig. 905 Action of an electron-ray tube.

permits measuring bias (and sometimes erase) current with the necessary degree of precision.

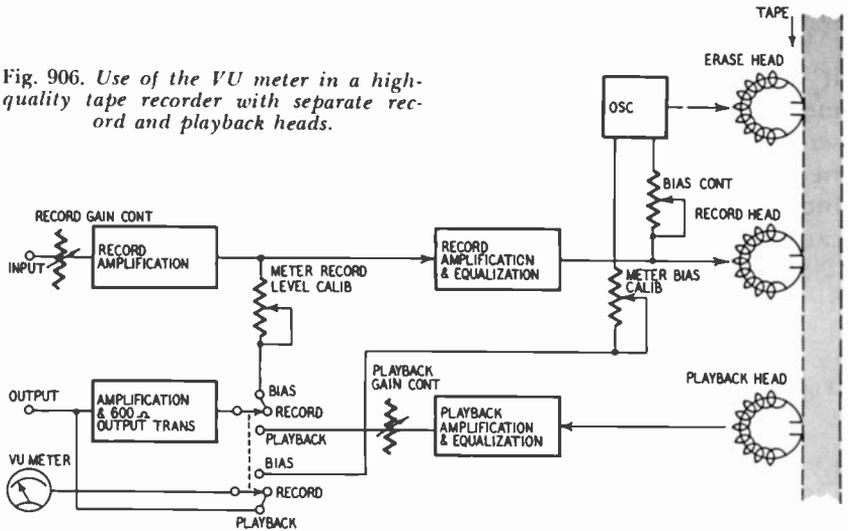
On the other hand, electronic indicators have several advantages besides lower cost. They respond immediately to changes in signal level so there is no problem of allowing for lag or overshoot. They read peak level, not average, and thus provide a truer indication as to when excessive distortion takes place. On the other hand, the experienced recordist, using a VU meter, can control level within about 1 db of that which would result from using a peak-reading indicator instead.

All told, because of ease of reading, indication of relative level, uniformity from one unit to another and ability to measure bias and erase currents precisely, the meter takes preference for use as a record-level indicator. And the VU meter takes special preference by virtue of its standardized characteristics and established role in the recording arts.

In professional work, a further important advantage of the meter is its ability to indicate the relative output level of the tape recorder. Professional tape recorders are used to feed program

lines in radio broadcast stations and to feed disc, other tape and film recording equipment. Not only is it worthwhile to know the original record level by observing playback level (an indication whether the tape was overrecorded, causing distortion, or whether it was underrecorded, resulting in an unnecessarily low signal-to-noise ratio), but it is even more important to be able to keep the playback level within a certain range right at the tape recorder to satisfy the requirements of following audio equipment.

Fig. 906. Use of the VU meter in a high-quality tape recorder with separate record and playback heads.

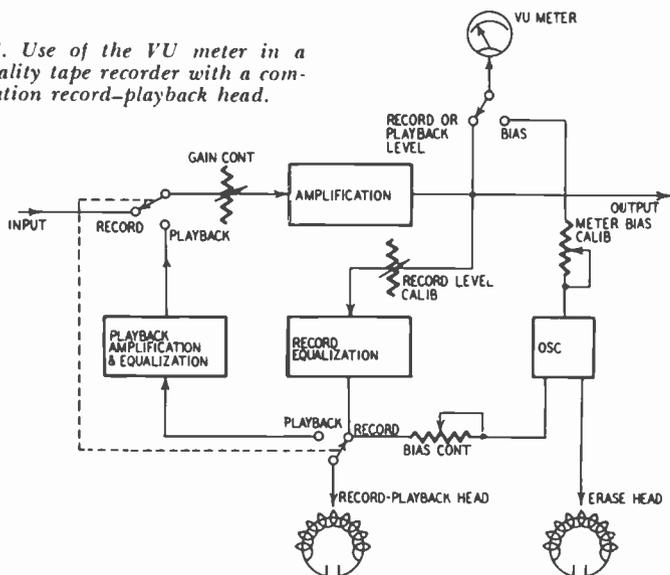


If the signal fed into the program line of a radio station is too low, there may be interference from other adjacent audio lines in the studio because of their relatively higher levels. Or the tape playback signal may be too small in view of the amplification capabilities of following audio equipment. Commercial studio equipment generally has at least 10-db reserve gain, but an occasional tape may come along which was recorded at so low a level that the following equipment cannot amplify it to the extent necessary for broadcast or recording purposes. In this case the meter indicates the inordinately low level and the operator can turn up the recorder's playback gain control.

On the other hand, if an excessive amount of signal is developed in tape playback, this may produce crosstalk on other audio lines in the studio. Also, it may cause distortion or unnecessary compression in associated line amplifiers, which often do not have level controls. And compression itself generates a certain amount of distortion.

Thus it is apparent that being able to meter playback level is a valuable facility. Figs. 906, 907 and 908 show how provision is made for metering playback level in three representative high-quality tape recorders. In Fig. 906, where separate record and playback heads are used, the VU meter is directly across the final output stage, except when measuring bias, and is switched along with this stage between the signal being recorded and the playback signal. In Fig. 907, the same head is used for record and

Fig. 907. Use of the VU meter in a high-quality tape recorder with a combination record-playback head.



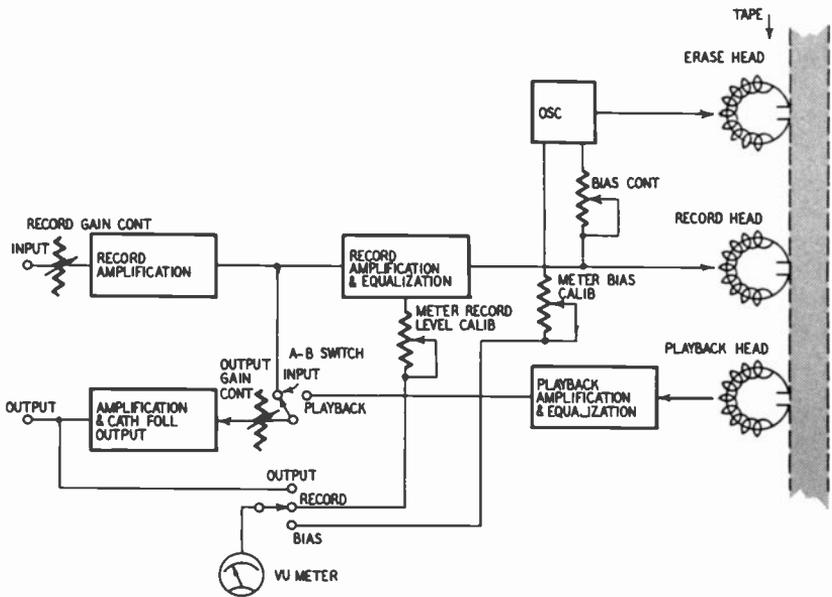
playback. Unless the meter is switched to read bias, it automatically reads record level or playback level, depending upon what mode the machine is in, because all signals go through the common amplification stage to which the meter is connected. Fig. 908, again for a three-head machine, employs a somewhat different setup which requires two switches to be positioned properly to read playback level; the meter switch must be connected to the final output stage, and this in turn must be connected to the early playback stages.

For the majority of home uses, the playback indication is of no importance. Therefore, moderate-price tape recorders permit the record-level indicator to function in playback only by inadvertence or for some purpose other than indicating playback level. If it does function, there is usually no meaning to the reading. Some manufacturers whose machines use an electron-ray tube

choose to have it remain on in playback and serve as a pilot light. Others allow the tube to operate only in record; thus it warns that the machine is in the record mode and helps guard against accidental erasure of a tape. For the electron-ray tube to operate only in record, it is necessary simply to supply its B-plus voltage from the same point as for the bias oscillator, which is always shut off in playback.

Drive circuits and requirements

Each of the basic types of indicator—meter, electron-ray tube and neon lamp—have considerably different requirements as to



circuitry and driving power. Therefore, the design of the tape amplifier must carefully take into account the type of indicator that is to be used. It is not feasible to change from one to another without making fairly extensive changes.

VU meter circuitry

A VU meter reads 0 VU when the meter is connected *directly* (without a 3,600-ohm resistor) across a 600-ohm resistance carrying 1 mw of power. The corresponding drive voltage is 0.774; by Ohm's law, $E = \sqrt{WR} = \sqrt{.001 \times 600} = \sqrt{.6} = 0.774$ volt. However, the VU meter requires a 3,600-ohm series resistor

to limit distortion due to nonlinear loading, and this necessitates a signal 4 db above 1 mw, namely 2.5 mw, to produce a 0-VU reading. The corresponding voltage is $\sqrt{.0025 \times 600} = \sqrt{1.5} = 1.23$. This, then, is the required driving voltage from a source having 600 ohms nominal impedance.

However, if a high-impedance source is used, say upward of 10,000 ohms, the VU meter would produce serious distortion due to loading, even with a 3,600-ohm external resistor. Furthermore, a considerably greater driving voltage would be required because of the loading effect of the meter circuit. Although the source may originally have presented 1.23 volts, the total impedance of the VU meter circuit is only 7,500 ohms (VU meter internal resistance of 3,900 ohms plus external 3,600-ohm resistor) and the loading effect is such that 1.23 volts is no longer available to drive the meter.

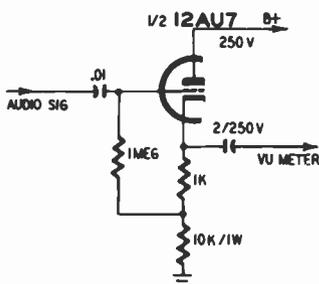


Fig. 909. Cathode follower suitable for driving a VU meter.

The proper way of connecting a VU meter is to place it (in series with a 3,600-ohm resistor) directly across a nominal 600-ohm line, as shown in Fig. 903. Thus many professional tape recorders have a 600-ohm output transformer, as represented in Fig. 906. The amplifier stage preceding this transformer may be connected to the record section so that the VU meter serves as a record-level indicator or to the tape playback section so that the VU meter serves as a playback indicator.

Fig. 908 represents a tape recorder with a cathode-follower output. The VU meter may be connected across this output to read playback level or, depending upon the position of the A-B switch for comparing incoming with playback signal, the meter can measure the incoming signal. However, the meter properly serves as a record-level indicator when switched to its record position,

where it is connected to a calibrated signal voltage from the record stage.

Occasionally one encounters a circuit in which the VU meter is not placed directly across the output but instead is driven by a special cathode follower. (Refer to Fig. 909.) The advantage is that the VU meter therefore does not load down the audio playback signal. Though specifications call for distortion produced by the VU meter to be no more than 0.2% harmonic, even this amount may be considered too much.

Volume-indicator circuitry

The volume indicator is driven to full scale, ordinarily, by a source impedance of 500 ohms carrying 6 mw of power. This

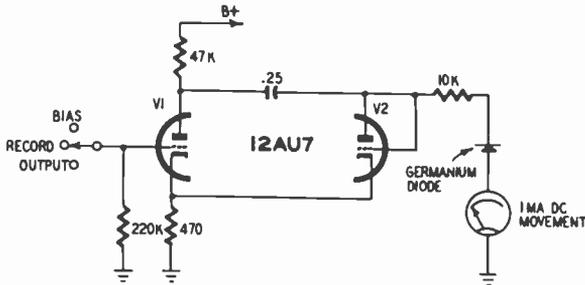


Fig. 910. *Vtm* type record-level indicator.

translates into a voltage requirement of 1.73 compared with 1.23 for the VU meter (using an external 3,600-ohm resistor). A 500-ohm output transformer or a cathode follower provides a suitable driving source. The volume indicator generally has an internal resistance of 5,000 ohms and is intended to be placed directly across an audio line without the use of a series resistor.

Vtm type indicator circuit

This record-level indicator employs a much less sensitive movement than the VU meter, generally a 0–1 millimeter. The required driving current is usually obtained by vacuum-tube amplification. Rectification of the audio signal is obtained through the use of a vacuum-tube diode, germanium diode or copper oxide rectifier.

Fig. 910 shows a typical circuit. V1 amplifies the signal being measured. The germanium diode serves as a rectifier for the meter. V2 is connected as a diode (plate and grid tied together)

and provides a shunt on positive halves of the cycle, thereby charging the 0.25- μf coupling capacitor. On negative half-cycles, the signal voltage at the plate of V1 is in series with the voltage charge on the capacitor, resulting in the sum of the positive and negative signal swings being impressed on the meter. This is, in effect, a voltage-doubler circuit, but it also behaves as a full-wave rectifier.

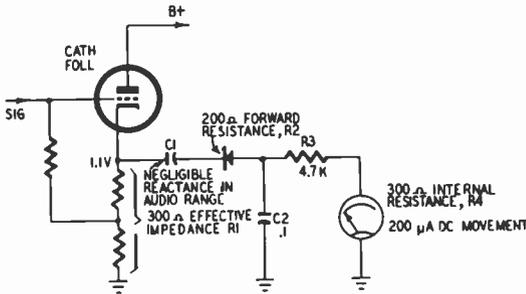


Fig. 911. Circuit of a peak-reading meter.

The cathode of V2 is across the cathode resistor of V1, and therefore has a positive voltage. Consequently, V2 does not conduct until the signal at the plate of V2 goes positive by an amount in excess of the positive voltage at the cathode. This permits V2 to behave somewhat in the same manner as the crystal diode which has a high forward resistance and therefore passes little current at low signal levels. The 10,000-ohm resistor is chosen to calibrate the meter.

Peak-reading meter

Fig. 911 shows a representative circuit for driving a 200- μa movement so as to read peaks. The signal is obtained from a cathode follower assumed to have 300 ohms impedance. The rectifier is a germanium diode having 200 ohms forward resistance. Thus, capacitor C2 is charged to 0.636 of its maximum value in a length of time determined by the time constant $C2(R1 + R2)$. For the values in Fig. 911, the time constant in microseconds is $0.1(300 + 200) = 50 \mu\text{sec}$. This is a short enough period for C2 to be charged by any waveform in the audio range. C2 cannot discharge through the rectifier. Instead, it discharges to 0.364 of its maximum value through the meter and R3 (a total resistance of 5,000 ohms) in a period determined by the time constant $C2(R3 + R4)$. Multiplying 5,000 by 0.1 yields a discharge time of 500 μsec . This

is slow enough so that most peak voltages impressed on C2 have time to produce an essentially proportional swing of the meter.

It may be noted that C2 cannot charge quite to the incoming voltage. R1 + R2 act as a voltage divider with R3 + R4. Therefore the voltage impressed on C2 is proportional to $5,000/5,000 + 500$, or 91% of the voltage supplied by the cathode follower. This represents a signal loss of less than 1 db.

Drive requirements depend upon the sensitivity of the meter. Although a 200- μ a movement is shown in Fig. 911, more or less sensitive meters could be used, depending upon the amount of signal available. Fig. 911 assumes that 1.1 volts is available. This

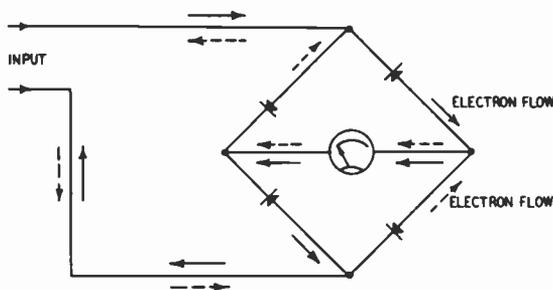


Fig. 912. Full-wave rectifier.

is sufficient, after voltage division, to drive the 200- μ a meter to full scale. The meter resistance R4 represents 300 ohms out of a total of 5,500, including R1, R2, R3, R4. Consequently, $300/5,500$, or approximately 5.5% of the voltage available at the cathode follower is impressed across the meter. And 5.5% of 1.1 volts is about 0.06. To drive a 200- μ a movement having 300 ohms resistance, the required voltage is $0.0002 \times 300 = 0.06$ volt.

In view of the relatively small load resistance presented to the negative half of the signal by C1, the rectifier and C2, the peak-reading meter circuit (as illustrated in Fig. 911) should not be connected directly across the output of a tape recorder. This might cause clipping of alternate signal peaks, thereby producing distortion. Instead, it should be driven by its own cathode follower.

Full-wave vs. half-wave rectifiers

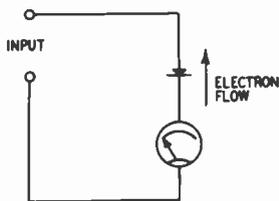
Before considering the circuitry of electronic indicators, it is advisable to pause briefly to consider the question of full-wave vs. half-wave meter rectifiers.

The VU meter contains a full-wave rectifier (Fig. 912). As shown by the arrows, electrons flow through the meter from right

to left on both the negative and positive halves of the input signal. The solid arrows represent negative and the dashed arrows positive polarity at the upper input terminal.

A simpler form of rectifier, the half-wave type, is shown in Fig. 913. Although less expensive, the half-wave rectifier has two disadvantages. First, since it passes only half the audio signal (either the positive or negative half of the waveform), the rectifier delivers only half as much current to the meter. This loss in sensitivity may require either a more sensitive meter or more amplification prior to the rectifier. Second, half-wave rectification

Fig. 913. Half-wave rectifier.



may not provide a true indication of level because speech and music waveforms are not symmetrical. As a result, the meter driven by a half-wave rectifier may somewhat understate or overstate record or playback level.

The electron-ray tube circuit

Although several other magic-eye tubes are suitable as record-level indicators, the 6E5 is most commonly used because of its low cost and relatively modest drive requirements.

Fig. 914 shows the 6E5 in a typical circuit. The electron stream flowing from the cathode to the target produces a circular fluores-

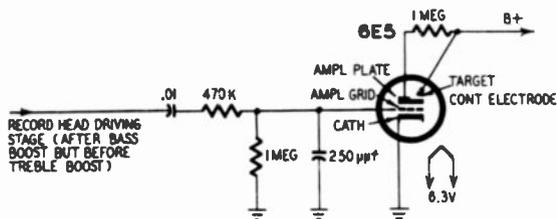


Fig. 914. Use of an electron-ray tube as a record-level indicator. (Pentron TR4)

cent pattern. A ray-control electrode deflects part of the electron stream so as to form a shadow, as shown in Fig. 905. This deflection electrode is connected to the plate of a triode amplifier within the same tube envelope. When the plate of the amplifier

goes positive due to a negative voltage on the grid, its deflecting ability decreases and the shadow partly or completely disappears. The 1-megohm and 470,000-ohm resistors in Fig. 914 form a voltage divider which provides the correct amount of signal to the 6E5 grid so that full closure of the eye corresponds to maximum permissible recording level. Between -6 and -8.5 volts are required at the grid to close the eye. Signal voltages well in excess of this amount are readily found in the tape amplifier when it is in the record mode.

In the circuit of Fig. 914, the electron-ray tube is constantly and rapidly flickering and therefore somewhat difficult to interpret. To provide a "floating action" which permits the eye to maintain its shadow size for a suitable fraction of a second, a circuit along the lines of Fig. 915 is often employed.

This circuit is basically similar to that of Fig. 911. The time constant of R2 and C3 permits C3 to be charged on negative

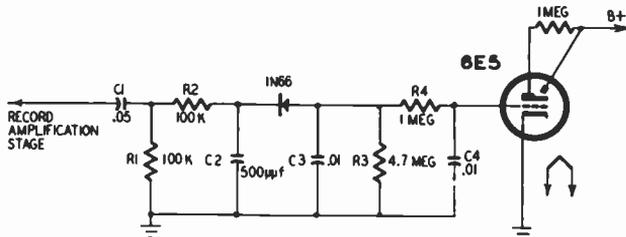


Fig. 915. Use of an electron-ray tube as a record-level indicator with "floating action." (Viking RP61 tape amplifier)

signals through the 1N66 in about 1/1000 second. But C3 must discharge through R3 because the 1N66 has a very high back resistance. The time constant of C3 and R3 is about 1/20 second, which means it takes that long for C3 to discharge. Thus the magic-eye reading is maintained for a period long enough so that the human eye can follow. Further smoothing action is provided by R4 and C4, which filter fluctuations above 16 cycles; in other words, they tend to maintain a discharge period of about 1/16 second.

The 1N66 germanium diode is used in Fig. 915 because it has a very high back resistance, that is, high compared with a 4.7 megohm resistor. A more familiar type such as the 1N34 has considerably lower back resistance and therefore would not be suitable. Some tape recorders, to obtain the necessary back resistance, use a vacuum-tube diode. Often a spare half of a dual triode is used, the plate and grid being tied to form a diode.

The neon lamp

Where a neon lamp is decided upon as a record-level indicator, the NE-51 is commonly used. Approximately 90 volts are required to fire the gas in the lamp. The lamp continues to glow until the voltage drops to about 60, so that there is somewhat of a built-in floating action. In certain tape recorders there is a high enough signal voltage available in the record amplifier to fire the NE-51. In other cases, the difference between the available signal voltage and the firing voltage is made up by applying about

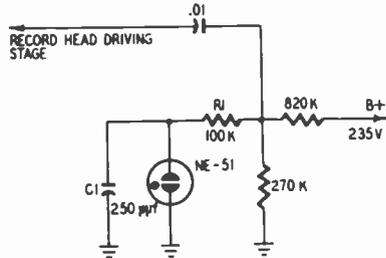


Fig. 916. Use of a neon lamp as a record-level indicator. (Pentron CT-1)

40 or 50 volts of B plus to the lamp so that it is necessary to obtain an audio signal of only 40 or 50 volts to actuate the lamp.

Fig. 916 illustrates the latter method of driving the indicator. The 820,000- and 270,000-ohm resistors form a voltage divider which applies the proper amount of B plus (about 50 volts) to the NE-51. Positive halves of the audio signal, obtained from the stage that drives the record head, raise the voltage across the NE-51 to about 90.

In some tape recorders there is sufficient amplification of the audio signal to supply the 90 volts required to fire the NE-51. The reader may well wonder how it happens that audio voltages reach such a level. The answer has special interest because it is a good example of the interdependence of design elements.

Gain is expensive, and in a moderate-price tape recorder a high-inductance record-playback head is especially desirable because of its relatively great output in playback. On the other hand, when this head is used for recording, its high inductance requires the use of a large constant-current resistor in series with the head to prevent discrimination against treble frequencies. Resistors as large as 200,000 ohms are not uncommon and, to provide enough current to the record head, they necessitate a relatively high record voltage, sometimes great enough to ignite a neon lamp. Moderate-price recorders usually contain their own power amplifier and speaker for playback. In some circuits the power output stage,

typically employing 6AQ5 or 6V6 tubes, is switched in the record mode to drive the record head (a dummy load resistor is sometimes connected across the secondary of the output transformer to replace the speaker, thereby protecting the transformer). The required voltage for driving the record head is available at the plate of the power output tube. Where the power amplifier uses push-pull output, the voltage is taken from the plate of one of the tubes. This voltage may be sufficient to actuate the neon lamp without the aid of a biasing B-plus voltage.

Commercial-grade neon lamps do not all light at the same voltage. Consequently, when replacing a worn-out lamp, the accuracy of the record-level indication may change by several db. When recording at high levels, a further rise of 2 or 3 db can seriously increase distortion.

Although the neon lamp, on the whole, serves nicely enough to show the record level corresponding to maximum permissible distortion, it does not indicate whether recording is at too low a level. Even the electron-ray tube performs this service for the operator, although not as well as the meter type of indicator. Therefore a number of tape recorders employ a second ("normal") neon lamp, which fires at a lower signal level, say about 6 db less. The user sets record level so as to ignite the "normal" lamp as much of the time as possible without causing the "overload" lamp to light unduly.

Fig. 917 shows a special circuit employing two NE-51 lamps. In this case no dc biasing voltage is needed. The record head and the lamps are driven by a 6AQ5, which serves as a power amplifier in playback and amplifies both the audio and the supersonic bias signals during record. The 5–70 μf capacitors regulate the amount of bias signal applied to the lamps. This together with the audio signal lights them.

Loading distortion

Specifically in the case of the VU meter, the record-level indicator should not load down the signal being measured. Unless the impedance of the indicator circuit is considerably higher than the impedance of the signal source, the indicator load will cause the signal voltage to decrease, possibly to the extent where there is insufficient voltage to drive the indicator.

The VU meter, the volume indicator and various other record-level meters employ copper oxide or crystal rectifiers which have nonlinear characteristics. The impedance of these rectifiers

varies with signal polarity and instantaneous voltage. Taking the VU meter as an example, assume that as a result of varying rectifier impedance the meter circuit looks like a 7,500-ohm resistance fluctuating over a 10% range. If a 10% change in load resistance has a significant effect on the voltage of the signal source, which is the case if the load impedance is less than about 10 times the source impedance, the nonconstant load resistance will cause appreciable distortion. In other words, the signal voltage is being continuously modified by the 7,500-ohm varying load resistance.

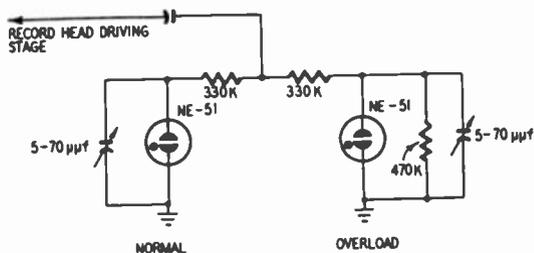


Fig. 917. Use of dual neon lamps as a record-level indicator. (Wilcox-Gay 4A10)

Such distortion may be negligible, less than 0.2% harmonic in the case of a VU meter connected in series with a 3,600-ohm resistor across a 600-ohm line. Ironically, the greatest distortion occurs at low signal levels, where the copper oxide and crystal rectifiers exhibit the greatest amounts of nonlinearity. In some circuits the IM distortion may be several percent at low levels.

Similarly, electron-ray circuits can produce loading distortion if proper measures are not taken. When the signal applied to the grid of the electron-ray tube goes positive, there is conduction between cathode and grid since the grid has no negative bias on it, the cathode being at ground (Fig. 914). This is equivalent to a low resistance load on the signal source during positive swings. When the signal goes negative, however, the effective cathode-grid resistance becomes infinite again. To limit distortion, a series resistor is used between the signal source and the electron-ray grid. It serves to keep the load resistance from going below a certain minimum and thereby prevents appreciable loading of the source. In Fig. 914 this series resistor has a value of 470,000 ohms.

Similarly, in the case of a neon lamp, its reduction in resistance when fired can load down the source; the change is from infinite resistance to about 100,000 ohms. Therefore a series resistor is

employed between the audio source and the neon lamp, as shown in Figs. 916 and 917 to keep the load from varying excessively.

Calibration of record-level indicator

At high record levels moderate increases in signal applied to the tape can produce relatively great increases in distortion. When the record level is high enough to produce about 10% IM distortion (acceptable for brief passages), an increase of 5 db in level can raise IM distortion above 30%. Thus, proper calibration of the record-level indicator is necessary. The indicator must be calibrated so that it gives a designated reading at the signal level corresponding to maximum permissible distortion. On the other hand, if the indicator is miscalibrated so as to indicate "overload" at a lower level, then the recording will have an unnecessarily low signal-to-noise ratio.

Professional recorders as a rule incorporate means for adjusting the record-level indication, while semi-professional ones occasionally do so too. Moderate-price recorders very seldom do. Instead they generally use fixed voltage dividers to regulate the indication level.

Fig. 906 shows the means provided by a typical professional tape recorder for adjusting the record-level indication. The signal going to the output stage and VU meter comes through a potentiometer which is adjusted so that the output level and meter reading correspond to a record level resulting in a specified amount of distortion, usually 2 or 3% harmonic. This potentiometer is adjusted at the factory. The user equipped with the necessary test instruments or a test tape can also adjust it. Figs. 907 and 908 show how other professional recorders provide for such calibration. In the case of Fig. 907, it is the amount of signal going to the record head rather than the signal to the VU meter which is adjusted.

Fig. 917 represents one of the rare instances in which a moderate-price recorder permits ready adjustment of the signal level at which distortion is indicated. The trimmer capacitors act as voltage dividers in series with the 330,000-ohm resistors at the bias frequency. The neon lamps are actuated not only by the audio signals but also by the bias signal, the amount of the latter being determined by the trimmer setting. The audio voltages at which the lamps should light are first determined and then just enough bias voltage is added by means of the trimmers to actually fire the lamps.

The electron-ray tube, neon lamp and peak-reading meter all read signal peaks and thus truly indicate when the record level is such as to produce objectionable distortion. However, the VU meter and other meter type indicators read only average rectified signal level, whereas it is the peak level that determines the maximum amount of distortion.

If the relation between peak level and rectified average level were constant, there would be no problem. Thus, a sine wave has a rectified average level about 4 db below its peak level, and, if only steady sine waves were being recorded, the VU meter could be adjusted to read 0 VU on the basis of a sine-wave input producing, say, 2% harmonic distortion. But typical program

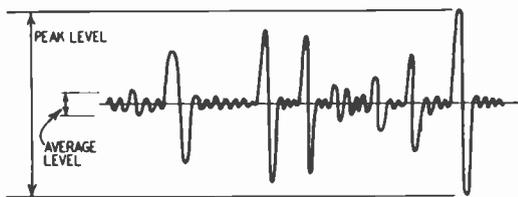


Fig. 918. Typical musical waveform as seen on an oscilloscope.

material has many transients which exceed the average level not by 4 db but by as much as 20 db (Fig. 918). These relatively tremendous peaks, though brief, can cause very severe distortion.

Consequently the calibration of a VU meter (or other average-reading meter) should be set to make allowance for the difference between average level indication and actual peak level. In many, though not all, professional tape recorders, some 6-10-db allowance is made for this. In calibrating the VU meter, it is set to read 0 VU for a sine-wave signal (usually 400 cycles) 6 to 10 db lower than that which produces maximum allowable harmonic distortion.

Even though the VU meter (or other meter) is calibrated with a reserve of this sort, the recordist cannot blithely adjust record level so that the pointer swings to a maximum of 0 VU. He must still exercise judgment and bring experience to bear. Different audio sources have different relationships between peak and average levels. Thus a maximum meter reading of 0 VU can result in overrecording in one case, while in another it may reflect an unnecessarily low recording level and hence too low a signal-to-noise ratio. For example, some organ music might have a ratio between peak and average levels not much greater than 5 db or so, whereas brass and percussion instruments might have

ratios as high as 20 db. Therefore, in setting record level on the basis of the meter reading, the recordist must make allowance for the type of material being recorded.

Moreover, in some types of program material a given amount of distortion is less objectionable than in others. For example, a relatively large amount of distortion can usually be tolerated in reproduction of speech. At the same time, speech often has relatively large transients. Thus, the need to allow for transients is more or less offset by the greater tolerable distortion. On the other hand, in different circumstances there may not be such an offsetting effect, but instead a need for all the greater caution on the recordist's part.

Finally, it is important to decide whether it is 1%, 2% or 3% harmonic distortion that is the maximum allowable amount. These relatively innocuous differences in harmonic distortion can mean vast differences in the amount of IM distortion. Thus, when harmonic distortion is at 1%, IM may be at 10%, which is acceptable, whereas IM may exceed 30% when harmonic distortion is 3%.

Circuit location

In many tape machines, including professional ones, the record-level indicator is connected to a point in the record amplifier where the audio signal has not yet been subjected to treble equalization, which ranges from a minimum of about 10 db to upward of 20 db at 7.5 ips. It may therefore be questioned whether an indicator so connected satisfactorily warns against distortion in the treble range. Essentially, the answer is that it does. Record treble boost largely affects the spectrum above 3,000 cycles, and in this area the decline of audio energy with rising frequency tends to offset the record boost. Moreover, for the same amount of distortion, somewhat greater signal levels can be applied to the tape at high frequencies than at low ones.

Of course, it is not certain that the decline in energy at the high end always compensates the record treble boost. To be safe, it is desirable to connect the record-level indicator to a point where treble equalization has been fully applied. Therefore some tape recorders, like the one illustrated in Fig. 908, connect the meter in this fashion.

On the other hand, many manufacturers, including some who make top-quality machines, have chosen to locate their indicators prior to record treble boost for several reasons: (1) Feeding the

meter from a point preceding high-frequency equalization achieves better isolation between the level indicator and the record head, helping in large measure to prevent bias current from producing an unwanted reading on the indicator. (2) Where a meter is used, if high-amplitude peaks of treble frequencies were fed to it after undergoing a substantial amount of boost, the meter might be damaged, particularly if the record level was accidentally set much too high. (3) Where a meter can be used to compare playback level with the incoming signal, proper comparison between the two would not result if the incoming signal were metered after treble emphasis but the playback signal were metered flat. On the other hand, as illustrated in Fig. 908, it is possible to circum-

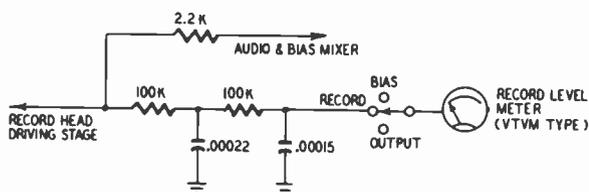


Fig. 919. Filtering network to eliminate bias pickup by record-level meter. (Concertone TWA amplifier)

vent this problem by a switching arrangement which enables the meter to measure the incoming signal either prior to or after equalization, the latter for purposes of record-level indication.

Whereas Fig. 908 conforms to the philosophy of metering record level after treble equalization, Figs. 906 and 907, reflect the opposite practice.

Bias pickup

Bias pickup may cause a meter, electron-ray tube or neon lamp to give an erroneous indication of record level. Bias current is of much greater magnitude than peak audio signals and its relatively high frequency range of 30,000 to 100,000 cycles causes it to display the radiation characteristics of radio frequencies; hence the chances of stray pickup are considerable.

Tape recorders must take measures to eliminate such pickup. Fig. 919 shows a two-stage filtering network used to prevent bias current from significantly affecting a meter indicator. This fairly elaborate precaution is required because the meter circuit is connected through a 2,200-ohm resistor to the stage where the audio and bias currents are mixed before going to the record head. In other recorders, however, where the indicator picks up the record

signal at an earlier stage, little or sometimes no filtering is necessary. In other words, there is least chance of bias pickup at points in the record amplifier farthest removed from the record head.

Figs. 914, 915 and 916 illustrate precautions taken against bias pickup in the case of electron-ray and neon-lamp indicators. In Fig. 914, the 250- μf capacitor between grid and ground has sufficiently low reactance at the bias frequency to act essentially as a short to ground. However, this capacitor in conjunction with the 470,000-ohm and 1-megohm resistors also appreciably reduces audio frequencies above approximately 2,000 cycles. On the other

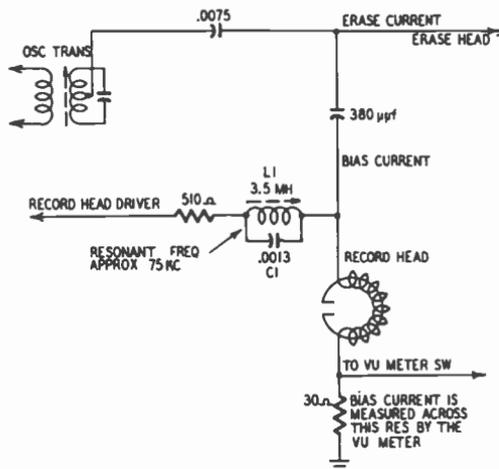


Fig. 920. Resonant trap for preventing bias current leakage. (Presto SR-27)

hand, most of the signal represents frequencies below 2,000 cycles.

In Fig. 915, the bias frequency is filtered by R2-C2. The time constant of these components also results in a significant reduction of audio frequencies above approximately 3,000 cycles. However, virtually all the fundamental frequencies and most of the audio energy occur below 3,000 cycles.

In Fig. 916, which illustrates a neon-lamp indicator, bias filtering is accomplished by R1-C1. Its cutoff frequency is such that only audio frequencies above 6,400 cycles are appreciably shunted to ground.

Fig. 920 shows an entirely different arrangement for keeping bias current away from the record-level indicator (a VU meter) and other parts of the record amplifier. L1 and C1 constitute a parallel-resonant trap with a very high impedance at the bias frequency and a relatively low impedance (due to L1) at audio

frequencies. Audio current can flow from the record amplifier through the trap to the record head. But bias current cannot flow to a significant extent in the reverse direction.

Metering bias and erase currents

Virtually every tape recorder which incorporates a VU or other type meter also uses it to measure the amount of bias current going to the record head (Figs. 906, 907 and 908). This is of fundamental importance because bias current affects distortion and frequency response and has a fairly critical optimum value. It is a decided asset to be able to check whenever desired whether bias is at a level previously determined to be correct. Such fac-

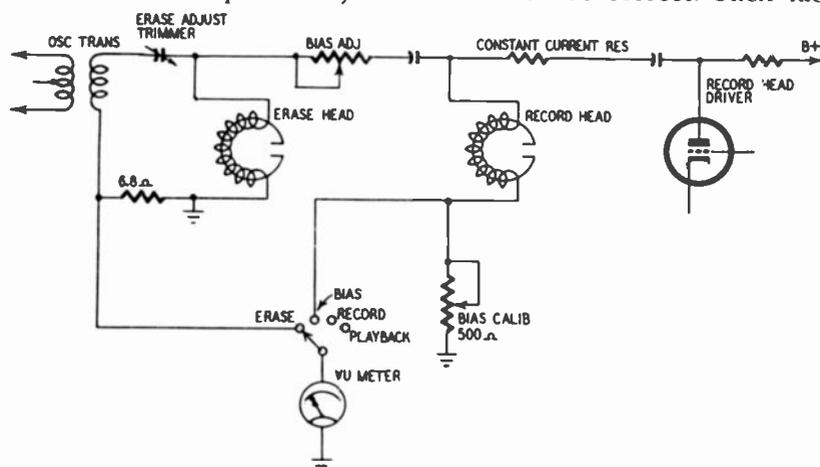


Fig. 921. Typical bias and erase metering circuit.

tors as aging of the oscillator or rectifier tubes, line voltage and warmup time can affect the bias level.

Unfortunately meter circuits are the only ones which make possible reliable readings at the high bias frequencies that are used—ranging upward of 30,000 cycles. Neither the electron-ray tube nor the neon lamp can be calibrated with sufficient accuracy to provide useful readings of bias current.

The most commonly used technique for the measurement of bias current is to insert a small resistor between ground and the record head's ground lead (Fig. 920), and to measure the voltage across this resistor. The value of the resistor is chosen so that enough voltage is developed across it by the proper bias current to produce a designated meter reading. Often an adjustable resistor is used for ready calibration.

Some of the top-flight professional tape recorders also provide for metering the oscillator current through the erase head, using a similar technique.

Fig. 921 shows a typical circuit for metering bias and erase current.

minimizing noise and hum

THE problem of subjugating noise and hum, ever present in audio circuits, is especially acute in a high-gain device such as the tape recorder. Although much that has been written on eliminating noise and hum in audio devices also pertains to the tape recorder, the subject is too important to be treated lightly or dismissed altogether in these pages on the grounds that it has been covered elsewhere.

In tape recorders it is generally the playback rather than the record mode which governs the amounts of hum and noise that are heard, assuming equal precautions are taken in each mode. Playback is ordinarily the limiting factor because of the relatively low signal levels presented to the input stage compared with noise and hum generated in this stage.

When recording from high-level sources such as radio tuners, TV sets, piezoelectric phonograph cartridges and audio control amplifiers, the input signal to the tape recorder is about 0.5 to 2 volts on peaks. Compared with hum and noise in the input stage, using a suitable audio tube, these levels are very substantial. When recording from a microphone, the available signal is considerably lower, about 10 to 30 mv on peaks. Yet in playback the signals presented to the input stage are still lower.

The peak playback signal is at most 10 mv, occurring in the region of 3,000 cycles at 7.5 ips. More likely, in a machine where record level is kept suitably low to confine distortion to reasonable bounds, peak output is about 5 mv. At lower and higher frequencies, output is much less than 5 to 10 mv.

Due to the fact that the playback head is a velocity device—output varies directly with frequency—the signal presented by the playback head to the input stage is a small fraction of 5 to 10 mv over much of the low range. Thus at 50 cycles the signal level is about 36 db below that at 3,000 cycles, or about 1/6 to 1/12 mv.

At the high end, two factors contribute to declining signal output above 3,000 cycles or so. First, the recorded frequency characteristic declines in the treble range. Second, there is a falloff in audio energy at the upper end of the spectrum. Altogether over much of the audio range the peak signals fed to the input stage of the playback amplifier approach 1 mv or less. This holds especially true at the frequency extremes, thereby accentuating the problems of noise and hum.

For the reasons just indicated, the following discussion will revolve about noise and hum that occur in the playback mode, chiefly in the playback amplifier. However, it should be understood that what is said applies equally to the record amplifier. The discussion will deal with principal sources of noise and hum and with means of combatting each. No reference will be made to mechanical noise produced by the transport mechanism, which is an entirely different subject. But electrical noise which originates in the transport and appears in the amplifier output will be discussed.

Sources of noise

For present purposes, noise may be defined simply as unwanted sound, other than 60-cycle hum and its harmonics. For the most part noise consists of evenly distributed frequencies, which include the audio range and beyond. At the high end of the audio spectrum there are more frequencies per octave¹ than at the low (for example, there are more frequencies between 5,000 and 10,000 cycles than between 50 and 100 cycles). Therefore noise composed of evenly distributed frequencies sounds high pitched or hissy. Noise may also include pops, crackles and other extraneous frequencies that may appear for one reason or another.

Random motion of electrons in a circuit causes what is known as thermal noise, increasing with temperature. The signal voltage produced by thermal noise is proportional to the square root of the impedance of the signal source.

Tube noise is chiefly of two kinds, thermal and microphonic.

¹An octave is a two-to-one frequency ratio.

Thermal noise refers to the random arrival of electrons at the plate. Microphonics refers to the fact that mechanical vibration of the tube results in minute changes in spacing between tube elements, causing variations in signal output, manifest as noise. The tube behaves as a microphone does, which produces a signal due to displacement of its elements.

The principal types of thermal tube noise are shot, flicker and partition noise. Shot noise refers to the fact that the flow of electrons from cathode to plate does not take place in a steady stream; the signal output of the tube reflects this variation in current flow. Flicker noise is similar, except that instead of covering the entire audio spectrum, as does shot noise, it is confined principally to frequencies below a few hundred cycles. The reasons for flicker noise are uncertain. Partition noise occurs in the case of pentodes and is caused by the division between plate and screen of electrons flowing from the cathode. Tube noise can also be caused by various tube defects, as in the case of a gassy tube or one with low leakage resistance between elements.

Thermal agitation of electrons causes resistors to be an important source of noise. Such agitation produces a minute current flow, representing noise. The larger the resistance, the greater the resultant noise voltage across the resistor.

Tape noise may be of several sorts. The principal offender is modulation noise. This arises from physical irregularities in the thickness of the base or coating as well as from magnetic irregularities in the coating. When an ac or dc magnetic field is applied to the tape, these irregularities are reproduced in the recorded flux and are equivalent to noise. An ac magnetic field is, of course, produced by audio currents in the record head. Sources of dc fields are magnetized heads and an asymmetrical bias waveform; the departure from symmetry in effect represents a dc component in the record and erase heads, with a corresponding dc field. Modulation noise caused by the audio signal varies in amplitude with signal levels. Modulation noise produced by a dc field is a more or less steady hiss.

Pops and crackles may occur because the bias waveform is not a pure sine wave but contains harmonic distortion. The principal offender in this respect appears to be second-harmonic distortion.

Imperfect erasure may be responsible for two kinds of noise. If the tape has previously been recorded, the erase-head field may not be sufficiently strong to remove completely the old signal, which competes in the background with the new signal, being

especially obtrusive during quiet passages of the fresh recording. On the other hand, erasure may be strong enough to remove all audible traces of the old signal, but, due to an asymmetrical waveform, it will produce modulation noise because of the effective dc produced by this waveform.

Print-through may be listed as a form of noise. The signal on one layer of tape may be magnetically transferred to an adjacent one because the recorded flux on the first layer passes through the adjoining tape. This effect is usually noticed only at relatively high recorded levels. Heat and length of storage tend to increase the effect.

The transport mechanism may cause clicks to be recorded on the tape due to sudden current surges when motors are switched on or off.

Tape recorders require a substantial amount of treble boost, and optimum design calls for all or nearly all this equalization to be supplied when recording. Treble boost should be used in playback only to the extent necessary to compensate for losses in the playback head (within reason). Some recorders, however, divide the total required treble boost equally between record and playback. The result is to emphasize not only the high audio frequencies in playback, but also tape noise and noise in the input stage of the playback amplifier.

Noise can be impressed on the tape in the form of a loud click or pop due to sudden application of plate voltage to the tube that drives the record head or due to sudden removal of this voltage.

Sources of hum

The playback head has an appreciable amount of inductance and is therefore susceptible to minute magnetic fields (caused by power-line current) which induce a corresponding hum voltage in the winding. This poses one of the most serious threats to satisfactory tape reproduction. Signal output of the head is so low in the region of 60 cycles that 70-db or more gain is required for amplifier output of 1 volt. Consequently, any hum induced in the head is greatly magnified.

Hum pickup by the playback head is mostly at the power-line frequency, ordinarily 60 cycles. However, harmonics of 60 cycles may also affect the head. For example, power transformers or motors, as well as their leads, radiate a substantial amount of third harmonic, namely 180 cycles.

In the tape amplifier, second-harmonic hum of 120 cycles can be a problem due to insufficient filtering of the B-plus supply. The

principal problem, however, is hum pickup at the grid of the first tube in the playback amplifier. Hum here is mainly 60 cycles, although harmonics may also be present in substantial quantity.

Hum pickup by the input tube of the playback amplifier may be due to a variety of factors:

1. Imperfect isolation appears between heater and cathode. Due to internal and external capacitances between these two elements, some coupling exists between heater and cathode. In the case of an ac-operated heater this can permit a significant amount of the 60-cycle voltage to reach the cathode. Since a tube will amplify an ac voltage at its cathode if the cathode is not perfectly at ac ground, the result may be a fair amount of hum in the tube's output. Similarly, there exists a leakage resistance between heater and cathode that can result in hum. Leakage resistance not only occurs within the tube but is also due to materials used in the socket, to materials used in the base of the tube and even to the insulation used on wires connected to the socket terminals.

Fig. 1001. Hum due to heater-cathode capacitive reactance.

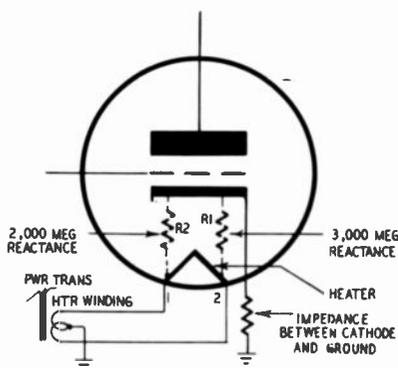


Fig. 1001 shows how hum may be impressed on the cathode by an ac-operated heater. Assume that at 60 cycles there is a 2,000-megohm leakage reactance due to capacitance from one end of the heater terminals to the cathode and a 3,000-megohm reactance from the other terminal to the cathode. These leakage reactances result in the cathode being nearer to the polarity of heater terminal 1 than terminal 2. In other words, due to unequal leakage reactances, the opposite polarities at the heater terminals do not cancel at the cathode. As Fig. 1001 shows, the center tap of the heater winding of the transformer is effectively connected to ground, physically or through a large capacitor. Thus there is a 60-cycle voltage between cathode and ground. The impedance

between cathode and ground acts as a voltage divider in series with the parallel leakage reactances (1,200 megohms) so that the larger the value of the cathode-to-ground impedance the greater the hum voltage at the cathode.

2. Imperfect isolation between the heater and grid results in heater-grid leakage resistance and capacitive reactance. As in the case of heater-cathode leakage, when heaters are ac-operated, an unbalanced resistance or reactance between each heater terminal and the grid results in an ac signal on the grid, with resultant hum in the tube output. The grid resistor acts as a voltage divider in series with the leakage resistances or reactances and, being usually in the order of 0.25 to 1 megohm, can result in a significant amount of hum voltage at the grid.

3. Current traveling through a conductor produces a magnetic field around it. If another conductor is in the presence of a changing magnetic field, a voltage will be induced in that conductor. Thus, the ac-operated heater coil produces a 60-cycle magnetic field which may cut through the grid and induce a corresponding voltage in it.

4. Hum may result from other magnetic fields affecting the grid. Motors, chokes, transformers and leads carrying substantial amounts of alternating current (heater and power-line leads) can produce such magnetic fields. A rectifier tube, such as a 5U4-GB, can sometimes produce a magnetic field—in this case changing at a 120-cycle rate—with sufficient strength to affect significantly a close-by low-level audio tube.

5. There may be sufficient capacitance between the grid, grid lead or other grid components and adjacent 60-cycle leads (heater and power line) to cause hum voltage to appear at the grid.

6. Hum may be picked up by a transformer connected between the playback head and the grid of the first playback tube. In some tape recorders using low-impedance playback heads which have a low output voltage, the signal is stepped up by a transformer before going to the grid. Transformers are sensitive to magnetic hum fields and, unless exceptionally well shielded and carefully mounted and oriented, they may be a potent source of hum. The same applies to transformers used with low-impedance microphones in recording.

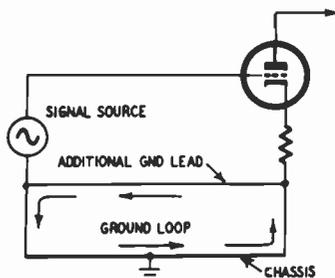
7. Hum may be due to an ac heater which is not effectively grounded at 60 cycles.

While this list includes most of the major sources of hum in a tape recorder, it is not all-inclusive. For example, hum may result

from a chassis voltage gradient. For instance, the chassis may be used as a conductor for 60-cycle current in place of one heater lead to each tube. As a result, there are voltage drops between various points on the chassis because the chassis does have some resistance. If the chassis is used as the ground lead for a low-level signal, then the 60-cycle voltage due to the alternating current and chassis resistance is included with the low-level signal and amplified along with it.

Another example is hum pickup due to a ground loop, which can occur when more than one ground return is used between two points. Assume there are two ground returns between a voltage source and a tube, as shown in Fig. 1002. These duplicate ground leads in effect form a shorted turn or ground loop. In the presence of a 60-cycle magnetic field a 60-cycle voltage is induced in the ground loop and is amplified by the tube. Simi-

Fig. 1002. Formation of a hum-inducing ground loop.



larly, there is the so-called wiring loop which results when the hot and ground leads of a signal source are too widely separated; these two leads, as in the case of a ground loop, form a turn in which a voltage can be induced by a magnetic field.

Although this discussion of hum sources has pointed at the first stage of the playback amplifier, it is obvious that a bad case of hum pickup in later stages can also affect performance adversely.

Combatting noise

In the matter of tube noise, there are four steps which can be taken by the designer (and perhaps by the user):

1. A tube type can be chosen which is known to possess good noise characteristics. But some tubes that are desirable with respect to noise may be undesirable with respect to other characteristics such as hum, distortion and gain. Consequently, a tube cannot be chosen on the basis of noise properties alone. However, a number of tubes are available, some of them developed specifically for audio applications, which tend to be generally satisfac-

tory. These include the 5879, 6SJ7-GT, 6J7-GT, the 6F5-GT, 12AX7, 12AY7, 6AU6, and foreign Z729, EF86, etc. Among these and several others the designer of a tape amplifier can find one that comes close to satisfying his particular requirements.

2. Although a given type may on the average be substantially less noisy than run-of-the-mill tubes, it is still usually necessary to employ a selected tube for the input stage. Sometimes the designer uses the input tube type for other stages as well, thus giving several specimens from which the owner can select the best for the input stage.

3. Noise produced by a tube varies with the manner in which it is operated. Shot noise varies inversely with transconductance (g_m)². Since g_m can generally be increased by operating the tube at moderately reduced heater voltage, such operation is a means of lowering shot noise. Shot noise also varies inversely with plate current. Thus noise can usually be minimized by increasing plate current within practical limits, which necessitates a high B-plus supply voltage and/or relatively low value of plate load resistor.

4. Tubes can be shock-mounted to minimize microphonics.

Noise due to thermal agitation in resistors can be reduced by using low-noise types, a characteristic usually associated with precision resistors. These are generally either deposited carbon or wirewound. Of the two, the wirewound are generally less noisy and more stable in value. Not all precision carbon resistors are deposited carbon, and therefore not all are low noise types. Some precision resistors are made from regular molded carbon ones by scraping away enough of the carbon to bring the resistance up to a specified value. Although this is not a common practice, it does occur.

Resistor noise can also be limited by using large-wattage values. Thus if a 2-watt resistor is used where a 1/2-watt one would ordinarily do, there is better dissipation of heat and consequently less thermal agitation. Even where no current flows, as in the case of grid resistors, high-wattage resistors tend to produce less noise.

The need for a low-noise type is greatest in the case of the plate load resistor. However, for best results, it is also advisable to use low-noise types as grid resistors and as unbypassed cathode resistors. What is sometimes done is to use a wirewound resistor as the plate load and deposited carbon units as grid and unbypassed cathode resistors. In subsequent stages, where the problem

²A lower heater voltage reduces the space charge (electron cloud) at the cathode. This means that the grid voltage has relatively greater effect upon the current flowing between cathode and plate.

is less acute, insurance against noise can be purchased at relatively little increase in cost by using 1- or 2-watt resistors as plate loads.

Wirewound resistors should be of the noninductive type, otherwise there may be some induced hum pickup. Making a wirewound resistor so that winding inductances cancel is a fairly complex procedure; moreover, at high ohmic values the only wirewound resistors generally available are precision ones—which helps account for their costliness.

Tape noise due to head magnetization may be avoided in part by circuitry that prevents sudden introduction or removal of audio, bias or erase currents through the record and erase heads, causing magnetization. The same measures also prevent clicks or pops being recorded on the tape due to such current surges. Fig. 1003 shows a typical circuit that causes B plus to be gradually applied to or gradually removed from the oscillator and record-head driver stages when switching between the record and playback modes. When switching from record to playback, electron

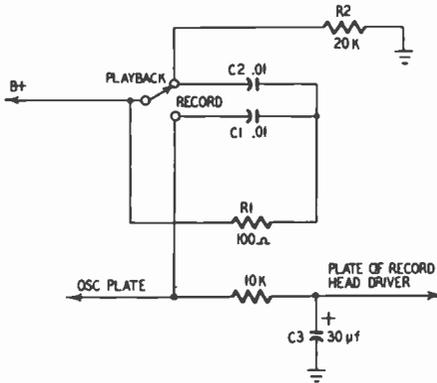


Fig. 1003. Method of preventing switching transients.

flow in the record-head driver and oscillator circuits continues briefly through R1 and C1 into the B-plus line until C1 is charged. When switching from playback to record, arcing is prevented at the playback terminal by the continued flow of electrons through R2, C2 and R1 into the B-plus line until C2 is charged. The plate voltage of the record driver stage rises slowly due to the time required to charge filter capacitor C3.

A further means of preventing head magnetization is for the oscillator waveform to be as close as possible to a pure sine wave, with a minimum of asymmetry; such asymmetry is in effect a dc component that magnetizes the head.

Some degree of head magnetization is inevitable, if only because of the natural asymmetry of audio waveforms. Therefore it is incumbent upon the user to demagnetize the heads occasionally with an electromagnet (powered by a 117-volt line) designed for this purpose. Too powerful an electromagnetic field may cause injury to a nearby record-level meter.

Where imperfect erasure is a noise source, the difficulty may lie in too high a record level, one productive of excessive distortion as well as insufficient erasure. But if the fault lies in the inadequacy of the erase head or elsewhere in the erase circuit, one way of bypassing this fault is to use a bulk eraser. However, if the tape is dual track, as is generally the case in home use, it is of course impossible to erase one track with a bulk eraser without erasing the other as well.

If print-through is the problem, it may be necessary to avoid excessively high record levels and to avoid storing tapes in places of high temperature or near magnetic fields. Print-through is a property of the tape rather than a fault of the recorder.

Noise on the tape due to switching transients can be avoided by placing capacitors across switches that actuate the transport motors, across relay contacts and the like. These capacitors prevent the sudden interruption of current flow, which may introduce transients into the tape amplifier.

Location and setting of the gain control can be a factor in controlling noise. Placement of this control at a relatively late stage in the amplifier means that cutting down signal level simultaneously reduces noise from the early stages as well. On the other hand, the control should not be so far from the first stage that signal levels become large enough to produce distortion.

In playback it is frequently best to operate with the playback gain control full on, if this is practicable and will not overload following equipment. This permits gain to be reduced in the following audio equipment, at the same time attenuating noise in stages following the recorder's gain control.

Combatting hum

Hum pickup by the playback head can be eliminated in large measure by enclosing the head in a heavy magnetic shield. Fig. 1004 shows a high-quality tape recorder equipped with such a shield. These are usually made of Mumetal and have openings just wide enough for passage of the tape. Magnetic fields in the vicinity of the head are shunted around the head by the shield.

Moderate-price tape recorders seldom employ massive and expensive shielding such as shown in Fig. 1004. Instead, they depend upon the shielding ability of the magnetic material in which the head is encased. A primitive but quite effective way of immunizing the head from magnetic fields is illustrated in Fig. 1005. Here a small piece of magnetic material (a silicon steel I-plate from a junked power transformer) has been placed near the record-playback head of a moderate-price recorder. The steel is about $\frac{3}{4}$ inch wide and 2 inches long after being bent double.

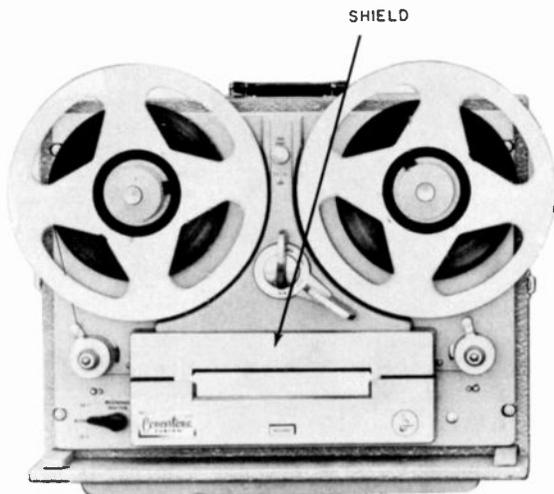


Fig. 1004. *Head shield used on professional-quality recorders.*

It clamps like a hairpin onto the bracket which holds the heads and guides the tape. The metal serves to warp the magnetic field surrounding the playback head so that fewer lines of force cut through it. The position shown in Fig. 1005 was determined by trial and error as the best feasible one.

Regardless of the type of shielding used for the heads, precautions should be taken to keep components producing substantial magnetic fields as far removed from the heads as possible. Sources of such fields include the power transformer, chokes, capstan and reel motors, and relays. Orientation of these components can substantially reduce hum pickup. Furthermore, the type and quantity of magnetic shielding used to enclose these components determine the amount of magnetic flux emanating from them.

Partly as a means of conquering the hum problem, most playback heads are equipped with dual windings, so wound that when they are properly connected in series not only is output aug-

mented but induced hum voltages tend to cancel (Fig. 1006). It may be seen that the two windings are in series so far as signal voltage is concerned but that the hum polarity is the same at both output terminals, resulting in little or no hum voltage.

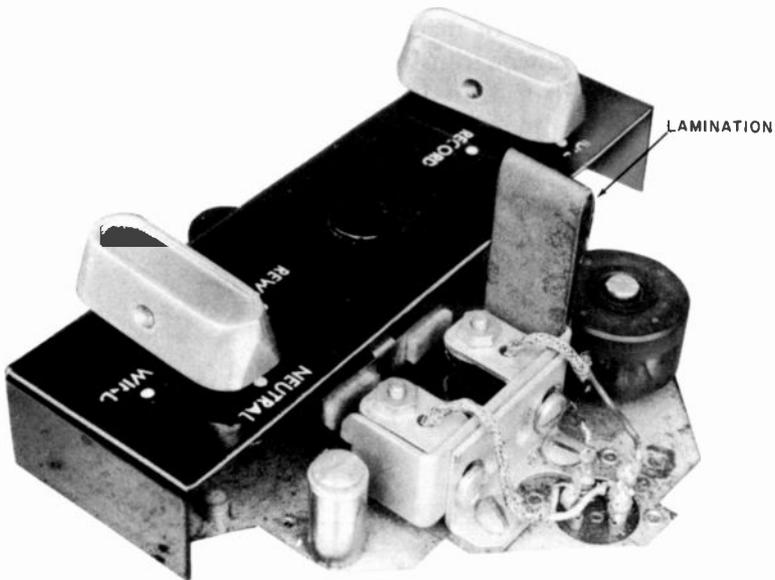


Fig. 1005. "Gimmick" used to minimize hum pickup by playback head of a moderate-price tape recorder.

Elimination of second-harmonic hum (120 cycles) in the amplifier requires fairly extensive filtering of the B-plus supply. Generous-size capacitors should be used, particularly in filter stages nearest the rectifier tube. B-plus supplies to low-level amplifier stages should go through three or four filter stages. Fig. 1007 illustrates a typical well-filtered B-plus supply.

Hum resulting from heater-cathode leakage resistance or reactance, heater-grid leakage resistance or reactance and the magnetic field produced by the heater coil (some tubes have a coiled heater to minimize hum radiation) can be obviated in part by choice of the proper input tube for the playback amplifier (and also, in addition, for the record amplifier). The 5879, Z729, EF86, 12AY7 and others are specially designed for audio applications, with hum as well as noise reduction a prime design consideration. Tubes such as the 6F5-GT and 6J7-GT have an external grid located at the top of the tube to remove the grid from hum sources.

The extent to which the tube is affected by nearby magnetic fields depends partly upon the tube itself and partly upon how it is situated with respect to components producing these fields. Tubes with metal rather than glass envelopes, such as the 6F5-GT, 6J7-GT and 6SJ7-GT, have built-in shielding against magnetic fields. Glass tubes in low-level stages should be protected by slip-over metal shields which make secure contact with ground. Care should be taken in design layout to keep power transformers, chokes, motors and the like a suitable distance from the input tube. A transformer mounted above a steel chassis rather than flush with it is likely to radiate less hum because when it is flush-mounted the chassis acts as an extension of the laminations, radiating hum. Aluminum chassis are preferable to steel in that they do not radiate hum and have lower resistance to circulating currents. Substantial benefits are sometimes obtained by putting the power supply on a separate chassis.

Sometimes a reduction in hum can be effected by demagnetizing the amplifier tube and its shield. Using a bulk eraser or other fairly powerful ac electromagnet, the tube and also the shield are brought into the magnetic field and slowly withdrawn. If the electromagnet is a very powerful one, do not bring the tube so close as to dislocate its elements.

Other things being equal, hum may be greater in a pentode than in a triode because the division of current between plate and screen of the pentode varies in step with a 60-cycle magnetic field. Triodes are less susceptible than pentodes to whatever 120-cycle hum may be present in the B-plus supply. Fig. 1008 helps explain why. The plate resistance of the tube and the load resistor form a voltage divider so that a portion of the 120-cycle hum voltage is present at the tube output. Since triodes have relatively low plate resistance—roughly 10,000 to 80,000 ohms compared with about 1 megohm for pentodes—the portion of the 120-cycle voltage that appears across a triode tube is less than that across a pentode. On the other hand, the possible need for an additional amplification stage, due to the lower gain of a triode, may offset the initial advantage of using a triode.

Heater-cathode leakage is aggravated by the fact that the cathode is usually at a positive potential, tending to attract electrons emitted by an ac-operated heater. An often-used countermeasure is to bias the heater with about 20 to 50 volts of B plus (Fig. 1009) so that the cathode is no longer positive with respect to the heater. Sometimes the heater is connected to the cathode of the power output tube in a tape recorder containing a power amplifier and

speaker. Furthermore, it is advisable to bypass the cathode with a large capacitor (a low-voltage electrolytic having several hun-

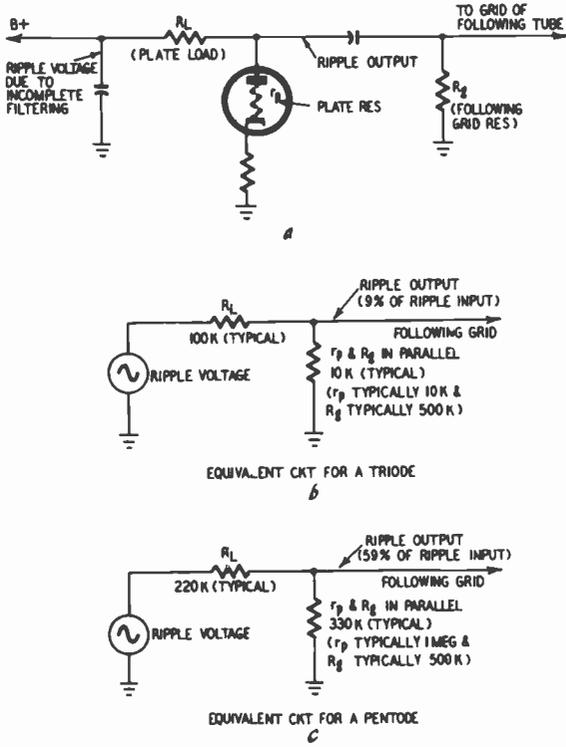


Fig. 1008. Reduction of 120-cycle hum by use of a triode.

dred microfarads capacitance) so that any 60-cycle ac at the cathode is completely shunted to ground.

Where heaters are ac-operated, the heater winding of the

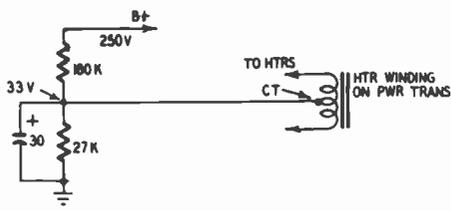


Fig. 1009. Typical method of reducing hum by putting dc bias on the heaters.

power transformer usually has a center tap which is physically grounded to balance out hum. Alternatively, the tap may be con-

nected to a dc potential, as was shown in Fig. 1009. The heater is still at ground so far as ac is concerned due to the large filter capacitor at the B-plus takeoff point. The theory behind the center tap is that, since the grid of the tube is also at ground through the grid resistor, hum voltages reaching the grid from the heater terminals are of opposite polarity with respect to ground and hence cancel.

However, it is not necessarily true that the grid is at ground so far as hum voltages are concerned. As illustrated in Fig. 1010, there may be leakage between the grid and a 60-cycle source, such as a motor, which results in a small amount of 60-cycle volt-

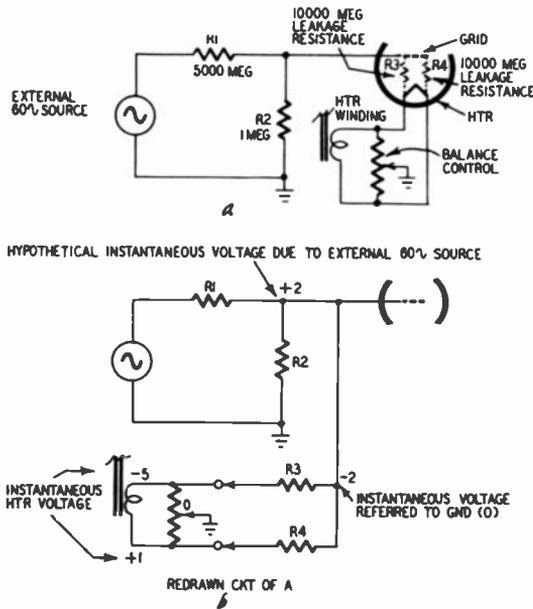


Fig. 1010. How the balancing potentiometer cancels hum.

age on the grid. Fig. 1010-a assumes a 5,000-megohm resistance between the ac source and the grid and also a 10,000-megohm resistance between each side of the heater and the grid. The grid resistor R2 is 1 megohm. R1 and R2 form a voltage divider, resulting in a small voltage at the grid. For easy illustration, assume that through leakage the external source causes +2 volts to appear on the grid at a given instant, although actually the voltage will be far less. The hum-balancing potentiometer shown in Fig. 1010 places an opposing voltage of -2 on the grid. Fig.

1010-b is a redrawn circuit showing how this is accomplished. The slider of the pot goes to ground so that the voltage at each heater terminal is referred to ground, or 0. Assume 6 volts across the heater and that the slider is positioned so the lower heater terminal, at a given instant, is $+1$ and the other terminal -5 volts. R_3 and R_4 constitute a voltage divider. Since they are shown equal, the voltage at the midpoint is halfway between $+1$ and -5 , or -2 volts, and has a source impedance of 5,000 megohms. Hence -2 volts is applied to the grid, balancing out the $+2$ volts impressed by another hum source. If R_3 and R_4 were unequal, then the slider would have to be positioned slightly differently to cancel the hum voltage at the grid of the tube.

If the slider in Fig. 1010 were returned to a B-plus point instead of directly to ground, as shown in Fig. 1009, nevertheless the large filter capacitor at this dc point would place the slider at ground so far as ac is concerned.

The hum voltage shown at the grid in Fig. 1010 does not necessarily arrive from an external source such as a motor, power transformer, etc. It may be due to heater-cathode and heater-grid leakage resistances and reactances or to the effect of magnetic fields upon the grid leads and grid resistor, etc. However, the hum-cancelling action is basically the same as that in Fig. 1010.

At all events, if an ac heater supply is used, the supply must

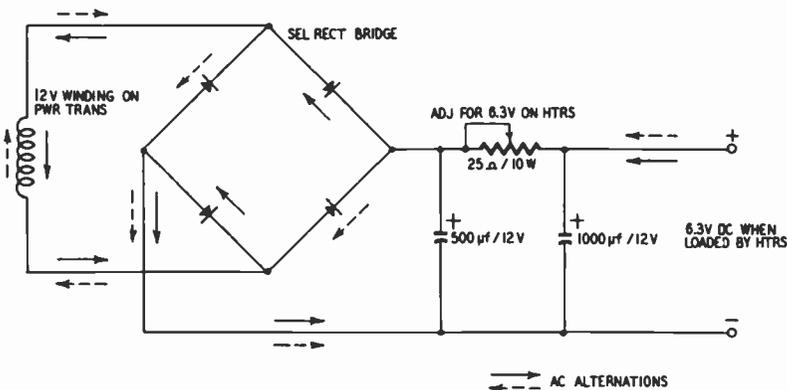


Fig. 1011. Typical dc heater supply.

be connected to ground in some manner because a floating heater will result in a relatively tremendous amount of hum. Stray capacitance or leakage resistance will cause high voltage ac present at the secondary of the power transformer with respect to ground to appear at the adjacent heater winding unless the latter is also at ground.

To prevent the heater from being a source of hum, a dc heater supply is often used (Fig. 1011). Although this is generally a very effective measure, it is not necessarily superior to an ac supply in conjunction with a hum-balancing potentiometer. If the heater and its leads are the only source of hum, then the dc supply may result in only a few db less hum. On the other hand, if external sources, such as hum pickup by the playback head, stray capacitance between the grid of the input tube and ac power leads, magnetic fields, etc., are causing an appreciable amount of hum to appear at the grid of the input tube, then the balancing potentiometer may have an advantage because it can also cancel hum due to these external factors.

However, the balancing potentiometer is effective only for 60-cycle hum. Harmonics of the 60-cycle frequency that appear at the grid will not be cancelled. Therefore, the potentiometer is not a cure-all. Neither is the dc heater supply. Thus, all possible measures of hum reduction should be employed so that hum is at as low a level as possible before the balancing potentiometer or dc heater supply is called upon to do its work. It is unwise to rely heavily on hum cancellation.

If ac is used on the heater of the input tube, a helpful measure against hum is to shield the grid pin of the tube from the heater pins. This can be done by mounting vertically a flat piece of metal, connected to ground, so that it isolates the grid pin from the others (Fig. 1012).

Adequate shielding of the signal lead from the playback head to the input grid is important. In moderate-price recorders, a shielded cable with a single inner conductor is ordinarily used. The shield wire should be connected to ground at an experimentally determined point near the input tube and not to a random position on the amplifier or transport chassis. A separate, heavy ground connection should be made between the transport and amplifier chassis if these are not an integral unit. In some recorders, to increase protection against hum, a shielded cable with two inner conductors is used. The two playback-head leads are connected to the two inner conductors, and one of these leads, together with the shield, is grounded at the amplifier.

Lines bearing alternating current should be dressed away from grids and other tube components, special attention being given to low-level circuits. Such lines, if traveling more than an inch or two, should be twisted so the magnetic fields surrounding each side of the line may cancel. The ac line should be dressed

against the chassis so that the latter can act as a shield for the field surrounding the line. Running ac leads along the corner of a chassis is especially desirable for two reasons: First, this increases the amount of contact with the chassis which acts as a shield. Second, it tends to maximize the distance between these leads and components subject to hum pickup. On occasion, running ac leads in a shielded cable may prove effective against hum.

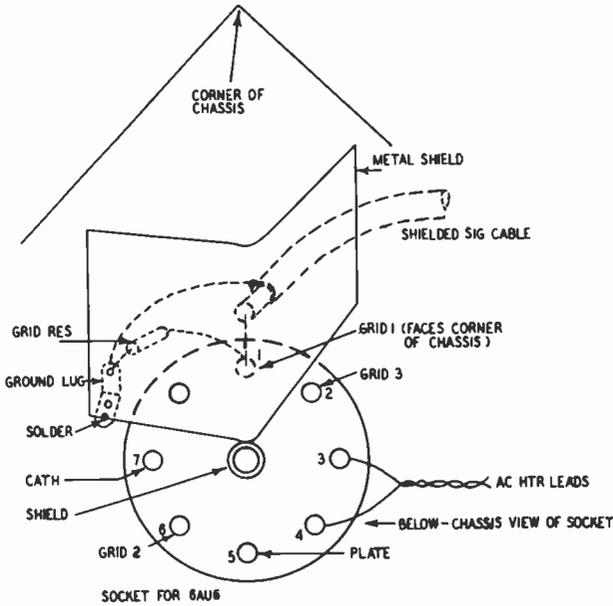


Fig. 1012. Shielding the grid of a 6AU6 input tube against hum.

Numerous measures can, and often should, be taken to minimize hum. A common ground point should be used for the low-level stages; sometimes a ground bus is used for the entire chassis. Leads, resistors and capacitors associated with low-level stages should be arranged as close to the chassis as feasible so that the chassis may serve as a shield for stray fields. The volume control should be separate from the power switch, although it is common practice in audio circuits to combine the two in one unit; the same injunction sometimes applies to the tone control, if any. A capacitor between one side of the power line and chassis may increase or decrease hum, depending upon which side of the line is involved. Reversing the orientation of the power-line plug in the line outlet often reduces hum a few db. A bottom plate for the amplifier can be helpful by acting as a shield with respect

to external fields. Putting the power supply on a separate chassis can achieve a substantial amount of hum reduction, although this is generally not necessary if the power transformer is well shielded and properly located and oriented. As a final example of hum-combatting techniques, some top-quality tape recorder design engineers have gone to the length of deliberately introducing hum of the proper amplitude and phase at some stage as a means of cancelling hum which other measures have failed to eliminate.

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