MAGNETIC RECORDING

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3M
COMPANY

THEORY OF OPERATION

FUNDAMENTALS OF MAGNETIC RECORDING

MAGNETISM. A magnetic effect exists in the vicinity of a wire through which an electric current is flowing. The wire is said to have a magnetic field surrounding it. If this field could be seen as light is seen, the wire would appear to be surrounded by a hazy glow. This glow would be brightest on the surface of the wire and would fade away as the distance from the wire increased. For a given current through a wire, a path of equal intensity or uniform glow could be traced around the wire, as shown in figure 1.

The lines in figure 1 are drawn to indicate the relative strength of the magnetic field surrounding one point on the wire. These lines are usually called lines of force. They should be thought of as extending along the entire length of the wire, surrounding it like a series of concentric cylinders.

If a compass is brought near a wire through which an electric current is flowing, the needle of the compass will swing in one direction or the other. The direction in which the needle swings is determined by the direction in which the current is flowing. For this reason, directional arrows are added to the lines in figure 1 to show that the magnetic field is polarized one way or the other.

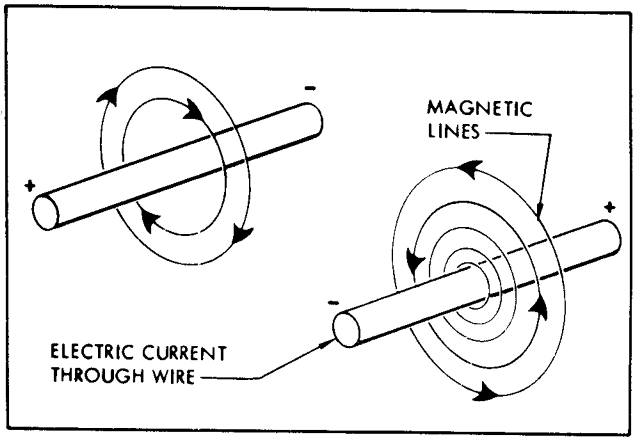

Figure 1. Magnetic Lines

The concentration of magnetic lines of force is greatly increased by winding many turns of wire onto a ring of iron or other material that has a special affinity for magnetism. See figure 2. Practically all the lines of force are contained within the ring. For this reason, a compass brought into the vicinity of the ring will not be affected. However, if an air gap is cut into the ring, as shown in figure 2, the field is exposed in the area of the gap. The intensity and direction of the field in the gap can be indicated by showing the reaction of a compass needle to it.

If the air gap is small and there are a large number of turns of wire on the ring, a very small current in the wire will cause an intense field of magnetism within the gap. The magnetic field, or flux, will increase or decrease when the exciting current is varied, and the polarity of the field

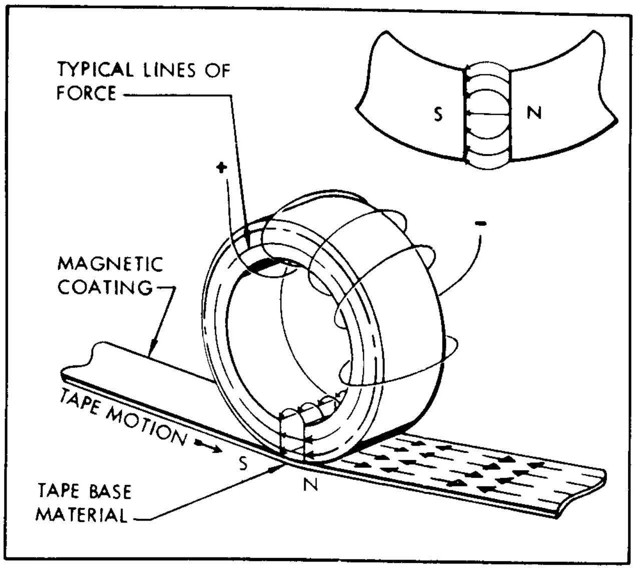

Figure 2. Record Head

will depend upon the direction of the current. The end of the broken ring from which the arrows emanate is called the north pole and the end of the ring where the arrows enter is called the south pole. These poles are reversed when the direction of the current is reversed.

Certain materials which are suitable for use as a magnetic ring or core permit the magnetic flux to vary proportionally to changes in the exciting current. Other materials may remain permanently magnetized after the current which causes the magnetism is turned off. In magnetic recording there are uses for each of these two types of materials.

THE RECORD HEAD. A magnetic tape recorder employs a device very similar to the ring structure previously described. In this device, which is called a record head, flux in an air gap varies directly with the current through its coil. The length of the gap in the record head is extremely small—in some cases less than one thousandth of an inch.

THE TAPE. A material that remains permanently magnetized is used in magnetic recording systems to record the flux variations in the record head gap. This material is usually a very thin layer of ferric oxide, coated on a mylar base tape. It is this metallic coating which receives and retains the magnetic image.

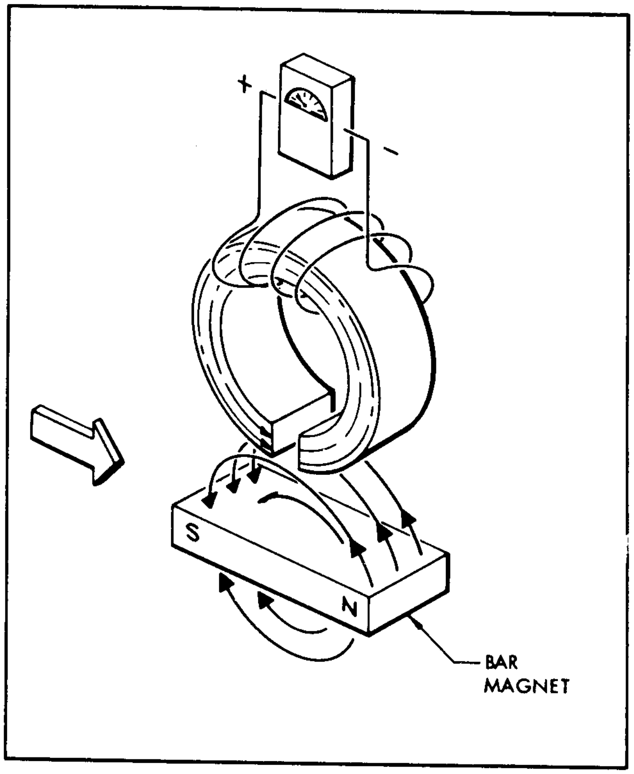

Figure 3. Reproduce Head

Tape is moved across the record head as shown in figure 2. It slides over the head in contact with the ring at the air gap. It is bowed slightly around the head to assure adequate contact at the gap. The tape lying beneath the gap is influenced by the flux in the gap. As illustrated in figure 2, each point of the tape experiences flux for a very short interval of time as it moves past the gap. In this manner, the tape retains along its length a magnetized impression of the current variations in the coil.

The process of creating a magnetic field with an electric current is reversible. Figure 3 shows a ring assembly, similar to the one previously described, with a sensitive ammeter connected across its coil. As a bar magnet is moved past the gap, the magnetic flux intercepted by the gap causes the meter needle to deflect to the right, indicating that an electric current is being produced. If the magnet were simply held close to the gap, but stationary, no current would be generated and the needle would stay in the center of the scale. If the magnet were moved past the gap in the same direction, but at an increased rate, the needle would deflect even further to the right. If, however, the magnet were moved past the gap in the opposite direction, the electric current would flow in the opposite direction from which it had been flowing, and the meter needle would deflect to the left. The magnitude of the current produced in the coil is proportional to the *rate of change* of magnetic flux experienced by the coil, and the direction of the current depends upon the direction in which the flux lines are flowing.

The magnetic impressions which have been recorded on the tape are sources of magnetic flux. Consequently, a varying electrical current similar to the one originally used to make a recording can be produced. To produce this current, the tape is passed over a ring similar to the record head, only with a current sensing device instead of a current source connected to its coil.

In principle, magnetic recordings are made and reproduced exactly as has been described. In a practical magnetic recorder, however, many refinements are necessary to insure that the reproduced signal is exactly like the one originally used to make the recording.

A BASIC RECORDER. Figure 4 illustrates a magnetic tape recorder in its simplest form. Sound entering the microphone is converted into an alternating electric current. This current flows through the coil of the record head and sets up on the tape alternatingly polarized, magnetized bits of information. Later, the tape passes the gap in the reproduce head and causes an alternating current to be generated in its coil. This current

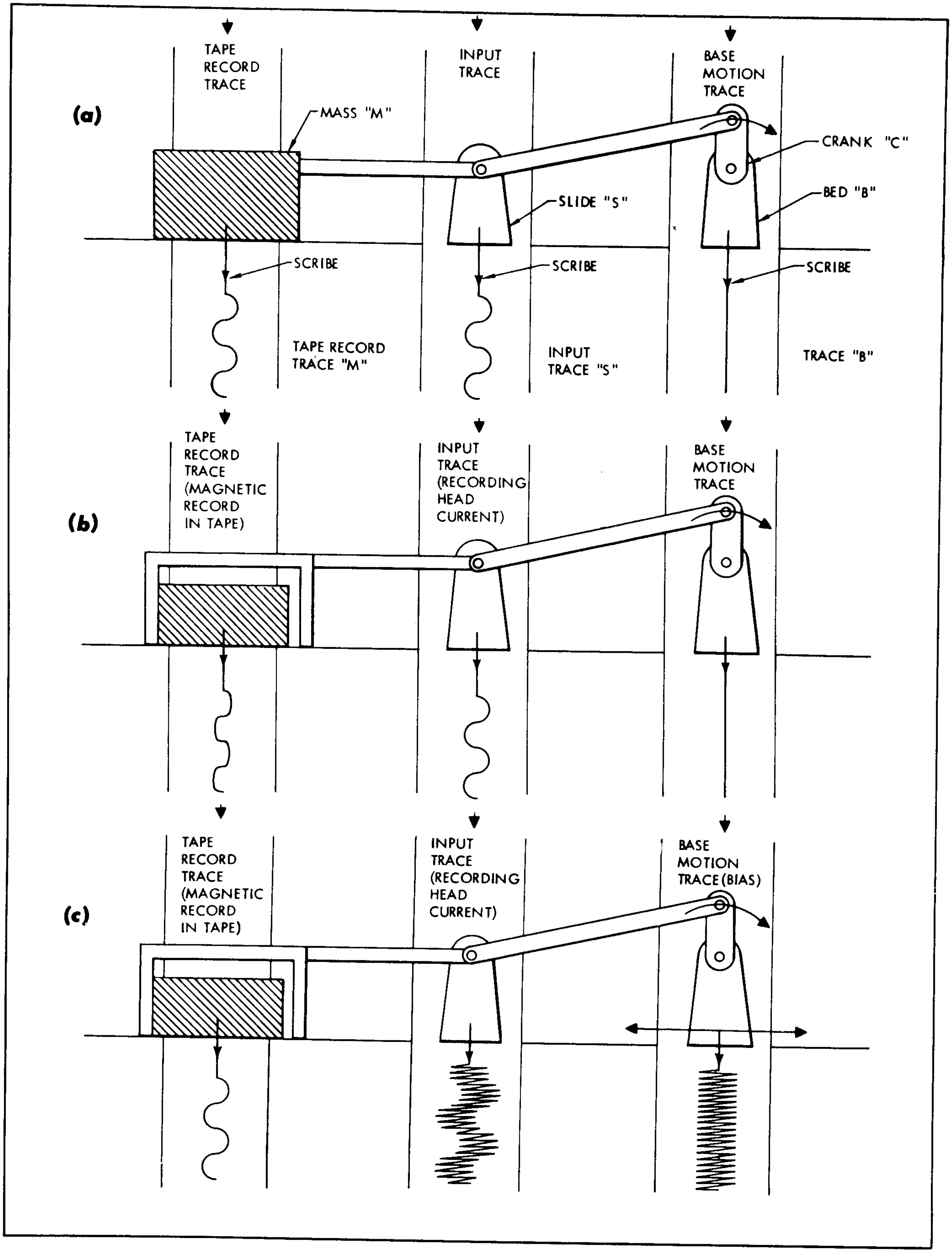

Figure 5. Mechanical Analogy

cycles) to be faithfully recorded. The only function of the bias frequency is to agitate the tape magnetically with sufficient force to take out the backlash. There is no intention of actually recording it on the tape.

AN ADVANCED RECORDER. Figure 6 shows the simple tape recorder of figure 4 after it has been modified by the addition of amplifiers and a source of high frequency bias. An amplifier "A1" has been added between the microphone and the record head. Both the output of this amplifier and the output of "B", a high frequency vacuum tube oscillator, are used to drive the record head. With this apparatus, it is possible to lay down along the tape a strong and faithful copy of the electrical currents which it is desirable to record. On playback, amplifier "A2" builds up the weak signals from the head sufficiently to make them operate a loudspeaker.

FURTHER REFINEMENTS—FREQUENCY RESPONSE DISTORTION. The device of figure 6 will give satisfactory results for some purposes, but the reproduction is lacking in smoothness of frequency response. Some frequencies in the audible range of 30 to 15,000 cycles per second are not reproduced as loudly as are others. Generally, extremely low and extremely high frequencies are more difficult to record and reproduce than those in between. This results in an attenuation at both ends of the spectrum which is noticeable to the ear. Figure 7 is a frequency response graph of the recorder/reproducer depicted in figure 6. The straight line "A" represents the intensity of sounds entering the microphone. The curved line "B" is a plot of the intensity with which various frequencies will be reproduced.

To make the reproduced sounds from this recorder similar to the original sounds, it is necessary to amplify different frequencies different amounts in accordance with a curve which is the opposite, or reciprocal, of curve "B". As indicated by curve "B", frequencies of about 10,000 cycles suffer such severe loss in intensity that they cannot be restored at all, and the correction for frequency response shown in curve "C", figure 7, can be carried only so far. A similar condition exists for extremely low frequencies, with the result that the over-all response of the corrected recorder/reproducer follows curve "D". While there is a rapid drop at the extremes, the most important part of the frequency spectrum is now reproduced with uniform response, closely matching the original curve "A". By means to be described later, frequency response can be extended as high as two megacycles or more.

CAUSES OF FREQUENCY DISCRIMINATION. Figure 8 shows a simple, but workable, recording circuit. Alternating voltages to be recorded are applied to the terminals marked "In-

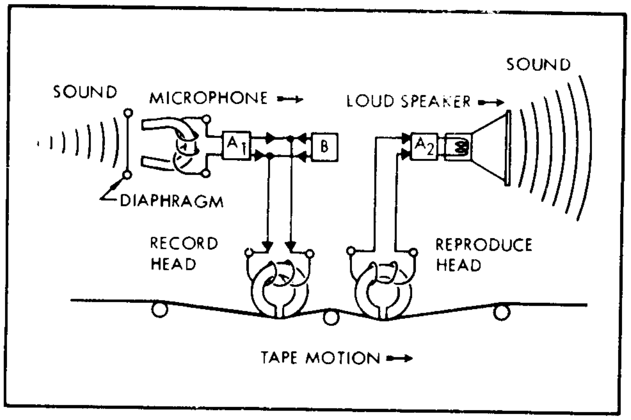

Figure 6. Advanced Recorder

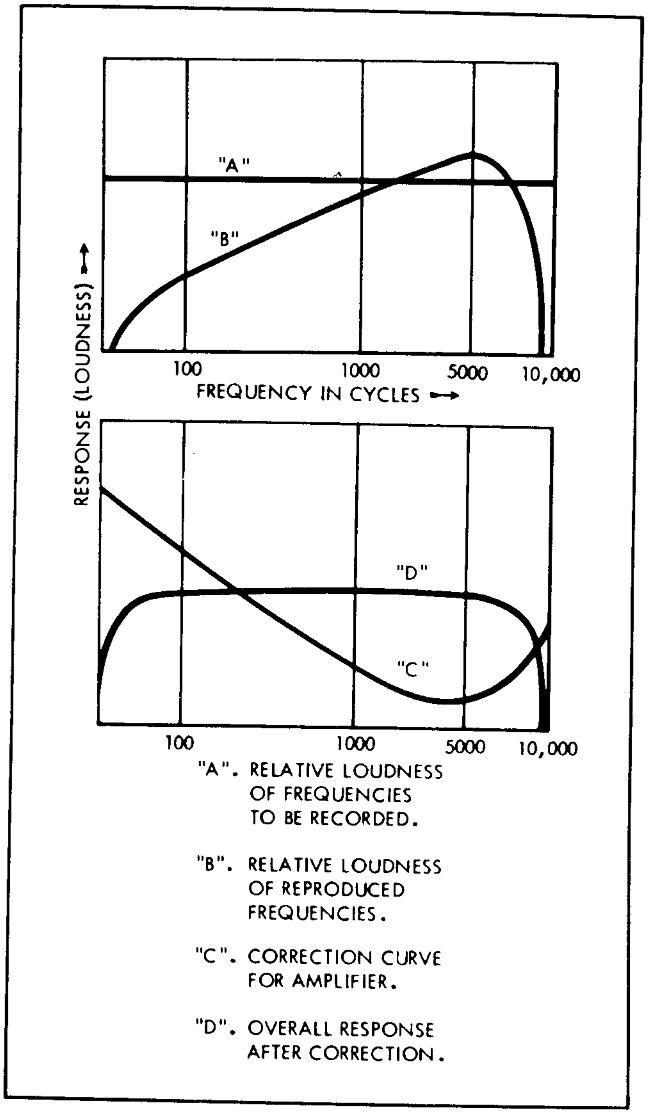

Figure 7. Frequency Response Graph

out". The current through the pentode vacuum tube varies directly in proportion to the input voltage. Since the record head is connected to the plate of the tube through a large capacitor, the current in the coil varies directly with the signal voltages to be recorded.

The pentode is used primarily to assure that the current in the record head follows the input voltage, regardless of frequency. Normally, if a source of constant voltage, but of variable frequency, is connected directly to a device like the record head, the current will decrease as the frequency increases. This is due to a choking effect caused by that property of a coil of wire known as its inductance. When the pentode is inserted between the input and the coil, the current through the coil becomes practically independent of frequency. The coil current, therefore, is determined only by the magnitude of the input voltage. If an alternating current of constant amplitude is used to drive a record head, a series of magnets is recorded in the tape as shown in figure 9. As the frequency increases, the magnets on the tape become shorter and shorter. Due to the constant current in the record head, however, the tape is uniformly magnetized, regardless of the length of any of its magnetic impressions. In other words, all magnets regardless of length are of equal strength because they are all generated by currents of equal magnitude.

When the tape passes the reproduce head, each of these magnets sets up an equal number of lines of flux in the head. The tape is moving along at a constant speed, so that a long magnet takes a greater time to pass the head than does a short one. Thus, longer magnets generate low frequencies and shorter magnets generate high frequencies. Since the current generated in the coil of the head is proportional to the *rate of flux change*, the long and short magnets do not produce currents of equal magnitude. The short magnets generate larger currents because they pass the gap more rapidly than the long ones. Consequently, the amplitude of the output signal is directly proportional to the frequency of the recorded signal. For example, the output signal at 3,200 cycles per second is 32 times as great as at 100 cycles per second. The effect of frequency on the output amplitude accounts for the long straight slope of curve "B" between 100 and 5,000 cycles.

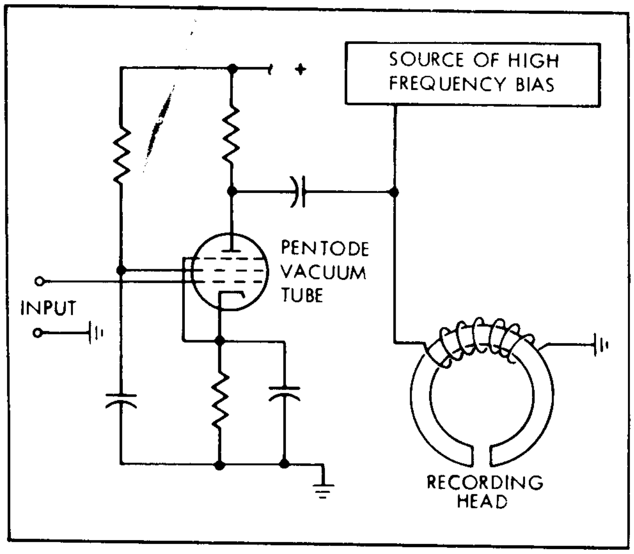

Figure 8. Simple Recording Circuit

CORRECTIVE EQUALIZATION.

SLOPE CORRECTION. This difficulty can be corrected in the reproduce amplifier by employing the network shown in figure 10a. A capacitor "C" acts as an open circuit, or infinitely high resistance to direct current, but as a resistor of finite value to alternating current. As the frequency of alternating current increases, the effective resistance (or impedance) of the capacitor decreases. With a constant voltage across the input terminals of figure 10a, the voltage across the output terminals drops as the frequency increases. Because "C" acts as a different size resistor for different frequencies, while "R" remains constant, the voltage is reduced in proportion to the radio between "R" and the effective resistance of "C". This device has a characteristic which is the opposite of that of the reproduce head and may be used to correct for the sloping portion of the response curve, line "B" in figure 7, lying between approximately 100 and 500 cycles.

CURVATURE CORRECTION. If another resistor is added to the network, as shown in figure 10b, then the voltage will no longer fall, but remain constant above a certain frequency. This helps correct for the curved portion of "B", figure 7, in the region of approximately 5,000

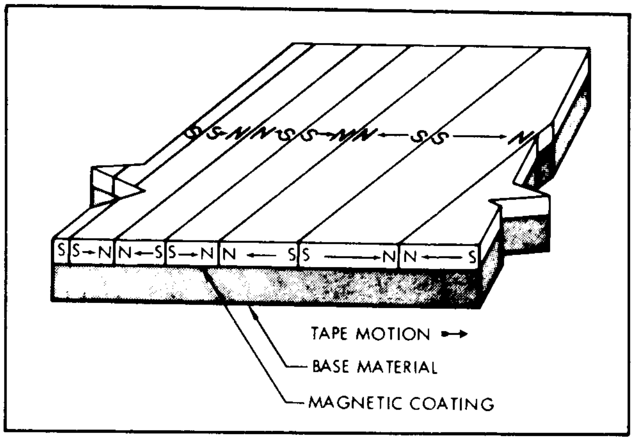

Figure 9. Tape Magnetization

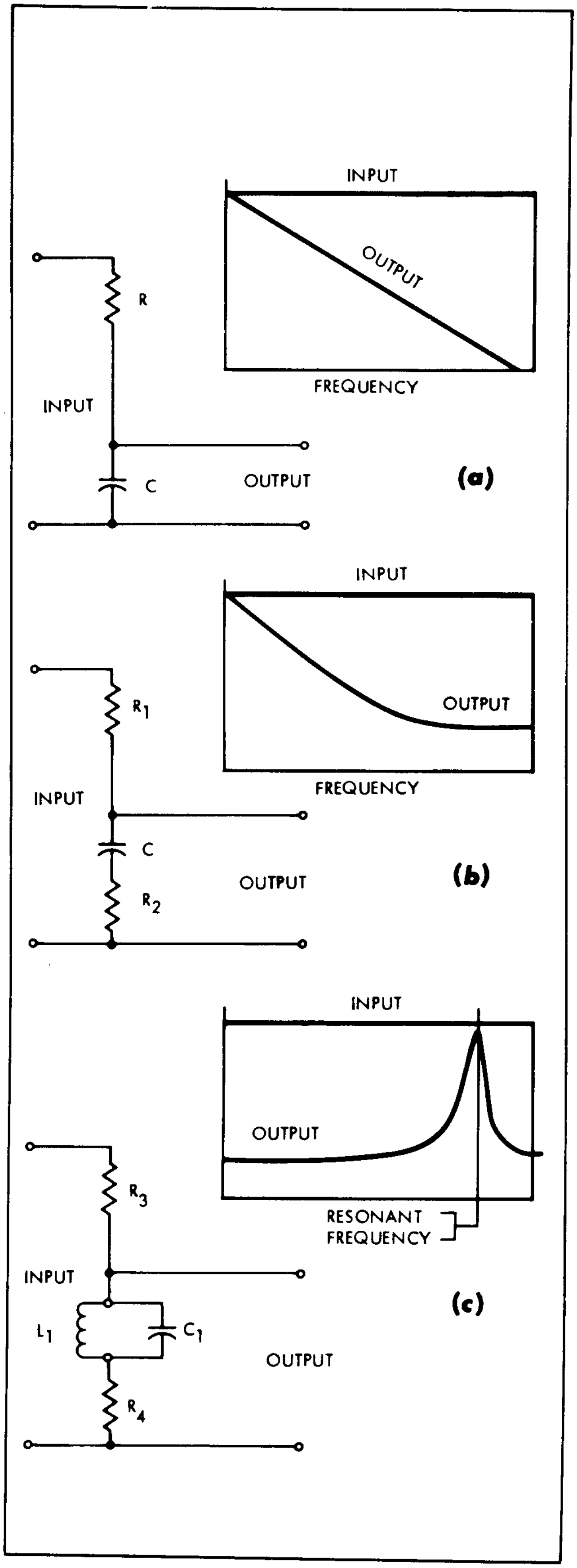

Figure 10. Corrective Networks

cycles. Above 5,000 cycles, however, the curve actually reverses direction. This often calls for another type of equalizer, one that causes the amplifier to have greater sensitivity at higher frequencies.

HIGH FREQUENCY LOSS CORRECTION. A high frequency loss correction network, together with its characteristic curve, is shown in figure 10c. At low frequencies, "L" acts as a very low resistance, and the output bears a relation to the input which is determined by the ratio of R3 to R4. The same is true at very high frequencies where "C" acts as a very low resistance. However, at some intermediate frequency, known as the resonant frequency, "L" reacts with "C" so that, in effect, their resistance is extremely high. For this reason, the output rises very sharply near resonance and is highest at the resonant frequency.

OVER-ALL CORRECTION. A network of this sort, used in conjunction with the network of figure 10b, will result in very effective correction for the rapid decay above 5,000 cycles in curve "B" of figure 7. By utilizing these networks, the corrective curve "C" in figure 7 can be readily made to match the loss curve "B". The over-all result will then approach that of curve "D". Since these corrective networks all cause losses, additional stages of amplification must be provided in the reproduce amplifiers.

GAP LENGTH LOSSES. Paragraph gave the explanation for the long straight slope of curve "B", figure 6, between 100 and 5,000 cycles. The reverse slope above 5,000 cycles is explained below.

Figure 11 shows the magnetized surface of a tape passing under a reproduce head. Six different positions of the tape in contact with the head are shown. The head is connected directly to a sensitive voltmeter. No equalization is included between the head and the voltmeter. The tape is considered to be moving past the head at a constant velocity.

In position 1, a long magnet is being scanned. The resulting low frequency produces a very low voltage. In 2, the magnets are somewhat shorter, and a higher voltage is generated because the frequency is higher. Similarly, in 3 and 4 the frequency and voltage are still higher. In fact, the magnet length in 4 is equal to the gap length of the head.

A higher output voltage cannot be obtained than that of case 4 because, as the magnets get shorter than the gap length, a condition like that at 5 is found. Here, one magnet lies well within the gap, but the adjacent magnet, of opposite polarity, also lies partly within the gap. The adjacent magnet's effect is to partially cancel the effectiveness of the first magnet. Therefore, the flux lines in the reproduce head cannot possibly be as dense as in 4, and the output voltage is reduced. In case 6 the magnets are still shorter, exactly two magnets being within the gap. Their net effect on the reproduce head is to generate no voltage whatever. This rapid drop in the voltage from maximum at 4 to zero at 6 occurs when the magnet length on the tape is cut in half. That is, in 4 one magnet fills the gap, and in 6 the magnets are just half as long. Therefore, we can conclude that if the frequency above the maximum output frequency is doubled, zero output will result. This effect accounts for the rapid loss in response in "B" of figure 7 above 5,000 cycles. This rapid drop can be compensated for to some extent by the resonant equalizer previously described so that the frequency response will be like curve "D" of figure 7.

GAP LENGTH VS. SPEED VS. FREQUENCY RESPONSE. It has been assumed in the above discussion of magnet lengths on the tape, that the reproduce head gap is of constant length. If the reproduce head gap is made just half as long, then the situation of case 6 becomes that of case 4. There now is a maximum output at twice the former frequency and it occurs where there previously was zero output.

By this theoretically simple expedient of cutting the head gap length in half, the frequency response has been increased two to one and, with modifications in the equalizer circuits, a response up to 15,000 cycles is now achieved.

There is also a direct relationship between frequency response and tape speed. If the tape speed is doubled, the frequency response is also doubled. Gaps in modern heads for sound reproduction are no more than 0.00025 inch long. Frequency response up to 2.0 megacycles may be achieved by the use of still shorter gaps and higher tape speeds.

However, there is much more to the problem of successfully recording and reproducing high frequencies than merely making the gap shorter and the tape velocity higher. Due to losses in the record head, it is difficult to design a system which will supply sufficient bias to the tape when the bias frequency is on the order of 7.0 megacycles.

Again, in machines of this type, extremely short gap lengths result in practically no flux interception by the head ring. Consequently, the voltage set up in the reproduce circuit is extremely small, and to obtain an adequate signal, the highest caliber amplifier commercially available is needed.

Record head gap length is not critical because the impression left on the tape at any point is the last one it receives as it leaves the influence of the gap.

SIGNAL-TO-NOISE RATIO. In a recorder, there is always a certain amount of noise in the background when the tape is reproduced. In a

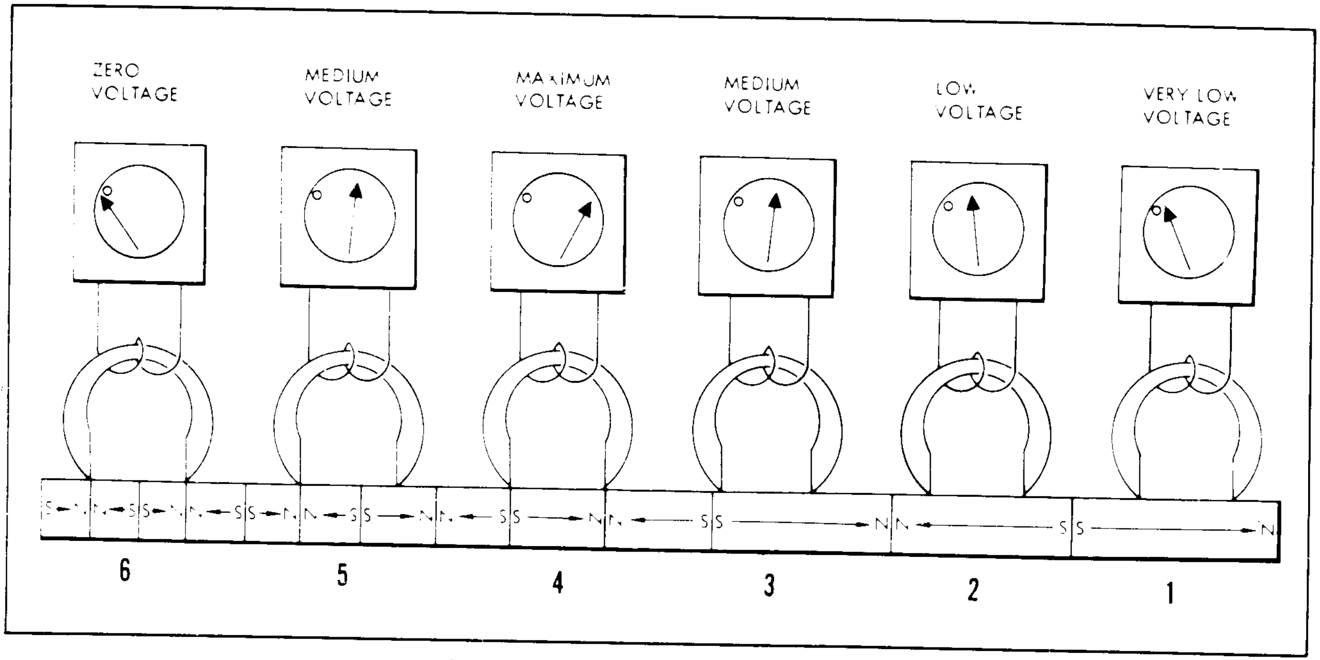

Figure 11. Gap Length Losses

good machine, this noise cannot be heard in the presence of even the weakest sounds which are to be reproduced. In a poor machine, the noise may be so high that only the very loudest sounds can be heard. The ratio between the strength of the recorded sound, commonly called the "signal", and the strength of the residual noise, is the signal-to-noise ratio. This ratio is expressed in decibels.

Most of the noise in a tape recorder arises from tubes, resistors and from alternating current fields caused by transformers and motors. There is also a certain amount of noise arising from the tape itself. This noise can be detected by listening with and without the tape in motion.

The signal-to-noise ratio is measured with relation to some standard intensity of recording on the tape. This intensity generally is that which will produce a known and measurable amount of distortion, such as "one per cent harmonic distortion".

TAPE SATURATION. There is a limit to the intensity to which a tape may be magnetized. If the current driving the record head is increased beyond a certain point, the tape does not retain any increased magnetic impression. Because of this, it is not possible to overcome excessive residual noise by recording the signal at a higher level. After the signal strength increases beyond a certain point, it is no longer faithfully recorded on the tape.

HIGH FREQUENCY PRE-EMPHASIS. By pre-emphasizing the high frequency components of speech and music, an improvement in signal-to-noise ratio may be achieved. Extremely high frequency sounds generally exist at low energy levels, so it is possible to boost their strength in the recording circuit without danger of saturating the tape. In order to make them sound natural when reproduced, it is necessary to pull them back down by means of a complementary equalizer in the reproduce amplifier. A complementary equalizer reduces the high frequency amplification, and in so doing, reduces the objectionable noise mentioned above. This results in an over-all improvement in signal-to-noise ratio.

ERASURE. A distinct advantage of magnetic tape recording is the property of tape which permits it to be erased and re-recorded. A piece of magnetized iron may be demagnetized by subjecting it to a decaying, alternating magnetic field. To provide this field, a coil of wire can be connected across an ordinary 60 cycle line source. If the piece of iron is inserted into the center of the coil, where the magnetic flux is most intense, and then slowly drawn out, it will experience a progressively weaker field until it is too far from the field to be influenced by it. As it is being drawn out of the coil, the iron will be magnetized in a different direction each time the polarity of the field reverses. As the field experienced by the iron is slowly reduced, its impression on the iron will slowly diminish until it makes no impression and the iron is demagnetized.

Magnetic tape is erased in the same way. An erase head is often included in the recorder for this purpose, but reels of tape can be bulk erased by placing them on a degausser, a device similar to the demagnetizer described above. The erase head is very much like a record or reproduce head, but it has a much larger gap. As the tape passes over the head, it is alternately saturated, removing any previous recording. As the tape is drawn away from the gap, the field it experiences gradually decreases until the tape is demagnetized. See figure 12. In a typical recorder, the erase head is placed just ahead of the record head, providing a single operation which removes the old recording and records a new one. In a high speed machine, it would be necessary to furnish the eraser with extremely high frequency current. Because it is difficult to obtain enough power at high frequencies, erase heads are not furnished on high speed machines and a bulk eraser must be used.

OTHER METHODS. Only one method of recording information onto magnetic tape has been covered in this discussion—magnetizing the tape in direct accordance with the amplitude of an input signal. Two other methods are, 1) the frequency modulation and, 2) pulse duration. These methods are used in instrumentation work, but are almost nonexistent in audio applications.

TAPE DRIVE MECHANISM. Any variation in tape speed, either when recording or reproducing a signal, will cause a distortion in the output. To reduce this distortion to a minimum, tape drive mechanisms are designed to reduce tape speed variations.

Figure 13 shows an elementary tape drive system. When a signal is being recorded or reproduced, tape speed variations are reduced by holding the tape against a capstan which turns at a constant velocity. Before reaching the heads, the tape passes over a roller with a flywheel attached to the roller's shaft. The flywheel helps filter out minor speed variations caused by variable friction in the supply reel spindle, tape scraping against the supply reel flanges, and by the tape being wound unevenly on the supply reel.

This elementary tape drive is called an open loop system because of the long open path of tape between the inertia idler on the left and the capstan on the right. For many applications, an open loop system does not maintain a sufficiently constant velocity. One of its inherent weaknesses is

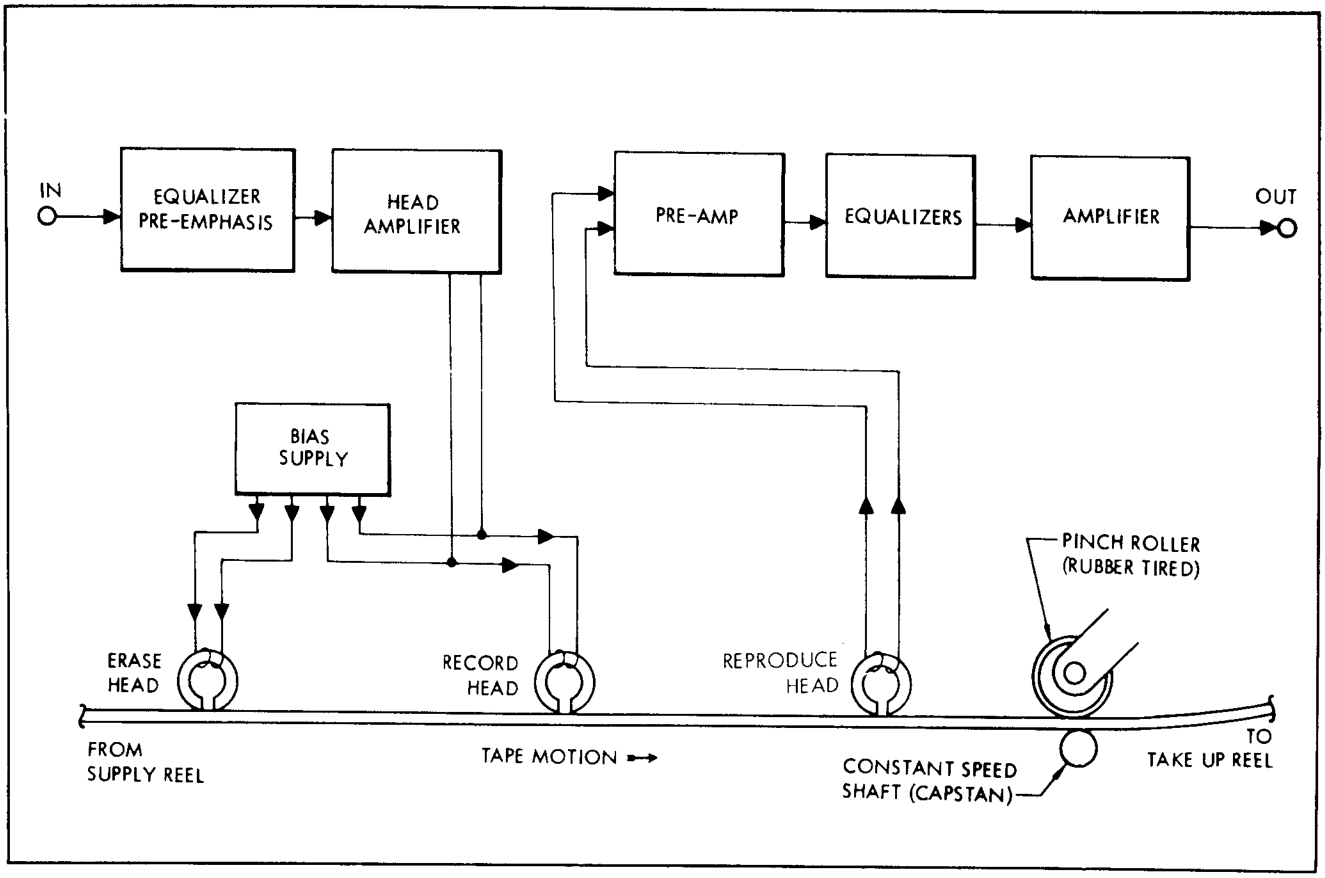

Figure 12. Typical Recorder/Reproducer

that friction between the tape and the heads sets up longitudinal vibrations in the tape. These vibrations can be reduced by shortening the length of the path between the inertia idler and capstan.

In figure 14, the tape in the vicinity of the heads has been formed into a loop around a reversing idler and clamped to both sides of the capstan. The result is that, instead of one long length of tape, there are two short lengths between the capstan and idler. The record head is placed in contact with one length, and the reproduce head with the other. This system is called a tight loop system.

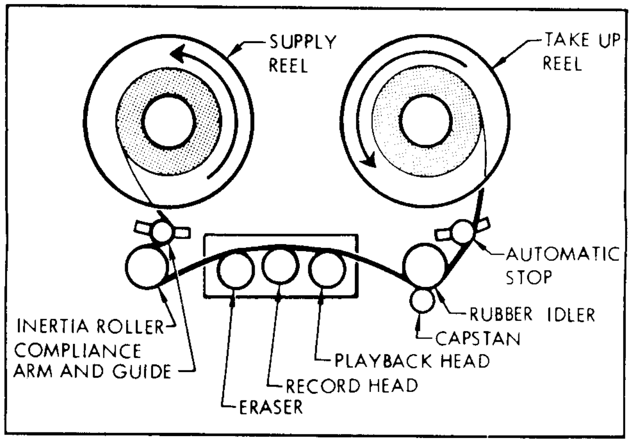

Figure 13. Elementary Tape Drive System

In a tight loop system, the loop of tape around the reversing idler is effectively isolated from the reels by being clamped at both ends to the capstan. If the capstan speed is held very constant, there will be minimum speed variation in the loop.

To keep the tape in the loop in contact with the heads, the tape must be held under slight tension. This tension can be provided by increasing the hold-back tension on the supply reel. Increasing the hold-back tension has one disadvantage, however. It tends to reduce the isolation at the capstan and allows vibrations to be transmitted from the reel to the loop.

A MINCOM development called the ISOLOOP drive holds the tape in the loop under slight tension without increasing hold-back tension. In systems using the ISOLOOP drive, the tape between the capstan and reversing idler is stretched very slightly—just enough to cause the tape to track properly over the heads. The stretching is accomplished by removing tape from the loop faster than it is being supplied. The cross-section

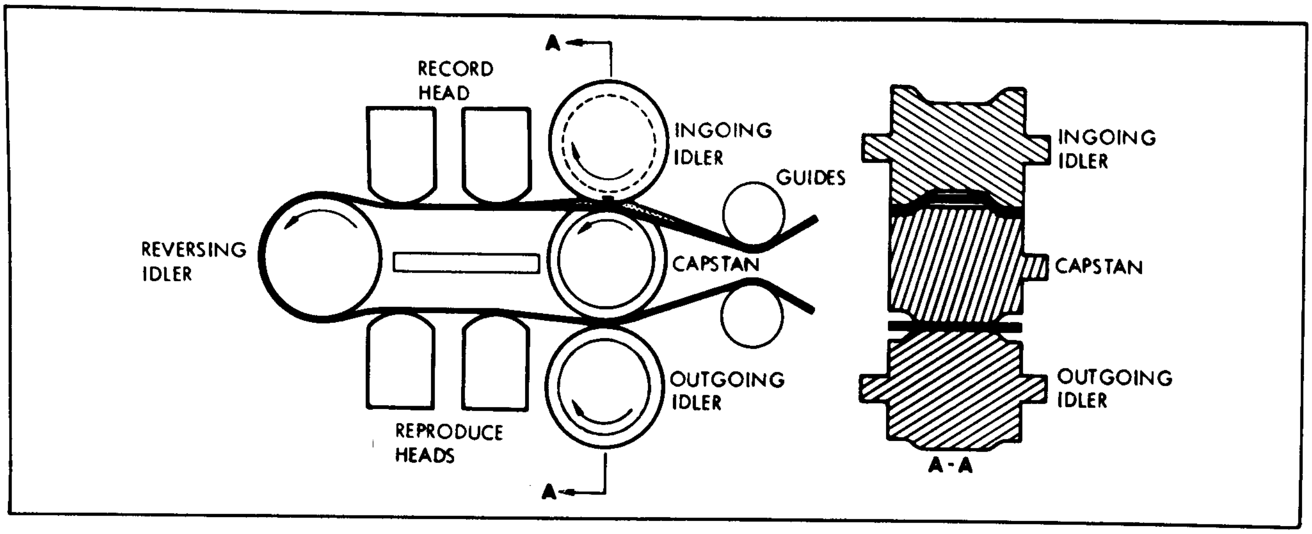

Figure 14. ISOLOOP Drive

in figure 14 shows the shapes of the capstan and capstan idlers. When entering the loop, the tape is held against the relieved edges of the capstan by the grooved idler, but when leaving the loop, it is clamped to the center of the capstan. Since the center of the capstan has a greater peripheral velocity than the edges, the tape must move past it slightly faster than at the edges. This velocity difference causes the elongation of the tape within the loop. The elongation is so slight that it is well within the elastic limits of the tape and causes no permanent deformation.