Chapter

6.1

Principles of Magnetic Recording

E. Stanley Busby

6.1.1 Introduction

Magnetic recording enjoys a rich history. The Danish inventor Valdemar Poulsen made the first magnetic sound recorder when, in 1898, he passed the current from a telephone through a recording head held against a spiral of steel wire wound on a brass drum. Upon playback, the magnetic variations in the wire induced enough voltage in the head to power a telephone receiver. Amplification was not available at the time.

The hit of the Paris Exposition of 1900, Poulsen's recorder won the grand prize. In this magnetic analog of Edison's acoustic recorder (which impressed a groove on a rotating tinfoil-covered drum), one whole cylinder held only 30 s of sound. In a few years, the weak and highly distorted output of Poulsen's device was vastly improved by adding a fixed magnetizing current, called *bias*, to the output of the telephone. This centered the signal current variations on the steepest part of the curve of remanent magnetism, greatly improving the gain and linearity of the system.

In 1923, two researchers working for the U.S. Navy first applied high-frequency ac bias. This eliminated even-order distortion, greatly reduced the noise induced by the surface roughness of the medium, and improved the amplitude of the recovered signal. Except in some toys, ac bias is used in all audio recorders.

Wire recording, further developed in the United States, found wide use during World War I1 and entered the home recording market by the late 1940s. Wire recorders had no capstan and pinch roller to establish uniform speed. Instead, a relatively large takeup spool, having a small difference between empty and full diameters, rotated at a constant angular speed. The wire speed therefore varied slightly between start and finish. As long as the change in diameter during playback equals the change during record, tonal changes did not occur.

A recorder using solid steel tape on large reels was developed in Europe. Licensed for manufacture by Marconi and others, it was used by European broadcasters before 1940. In some installations, a wire cage around the recorder protected operators from the consequences of breakage of the spring-steel tape.

Development of coated magnetic tape began in Germany in 1928. The first tapes consisted of black carbonyl iron particles coated on paper, using a technique developed by Fritz Pfleumer to bronze-plate cigarette tips. By 1935, Badische Anilin und Soda Fabrik (BASF), a division of I. G. Farben, had produced cellulose acetate base film coated with gamma ferric oxide. During the war years, the tapes used for broadcasting were a suspension of oxide particles throughout the thickness of the acetate. Beginning in 1939, polyester substrates, which have superior strength and tear resistance, replaced acetate.

During World War 11, German broadcasters used Magnetophons made by the Allgemeine Elektrizitat Gesellschaft (AEG). At the end of the war, a U.S. Signal Corps major, John T. Mullin, obtained two machines. Too large for a mail sack, they were dismantled and gradually shipped home to California in pieces along with 50 rolls of tape. Unlike the military field dictation recorders, which used dc bias, the machines used for broadcasting were equipped with high-frequency ac bias.

6.1.1a Development of Modern Recording Devices

In 1946, using modified electronics, Mullin demonstrated a Magnetophon at a San Francisco meeting of the Institute of Radio Engineers. Among the engineers attending the meeting were Harold Lindsay and Charles Ginsburg. Both men were to influence greatly the future of magnetic recording. Mullin and his partner William Palmer, a San Francisco filmmaker, took a machine to Hollywood to demonstrate it at the Metro-Goldwyn-Mayer film studios. Alexander M. Poniatoff, founder of the Ampex Corporation, then a maker of electric motors, heard a demonstration. In search of a postwar product, he determined then to develop a tape recorder. He hired Lindsay to lead the design team.

Mullin demonstrated his recorder to the renowned singer Bing Crosby. Recorded on disk, Crosby's Sunday-evening radio show had such poor sound quality that the sponsor began pressing him for live broadcast. Crosby disliked live broadcast intensely and hired Mullin to record the 26 shows of the 1947–1948 season. These were recorded on the captured Magnetophons by using the captured tape. Lacking confidence in the new technology, the American Broadcasting Company (ABC) transferred each show to disk for broadcast.

Contractual arrangements with others prevented Mullin from providing any circuit details to Lindsay. Nevertheless, Lindsay completed a prototype and demonstrated it to Crosby. Twenty recorders were ordered by the ABC network, saving the faltering company.

In the absence of wartime restrictions, applications of the new technology spread quickly. In 1949 performers Les Paul and Mary Ford pioneered the technique of recording multiple parts performed by one person. Recorders also were used to overcome the 3-h time displacement between the east and west coasts of the United States and Canada. Used as data recorders, they aided vibration analysis, medical research, and other endeavors involving signals occupying the audio spectrum.

At about 1950, the recording of a frequency-modulation (FM) carrier, or of a pulse-code-modulated signal, extended the low-frequency response to nearly zero. Recording of strain gauges, pressure sensors, depth sensors, seismic events, and other slowly varying signals became possible. Called *instrumentation recorders*, these machines were put to use in automotive test vehicles, flights of experimental airframes, submarines, and space vehicles.

In the 1950s, developments in magnetic recording diverged into separate, but related, paths, each growing within its own domain.

The professional audio recording industry developed multitrack recorders, portable audio recorders, electronic editing techniques, and machine synchronizers that could speed-lock one audio reproducer to other audio recorders, television recorders, or film cameras.

Several researchers extended the high-frequency response of magnetic recorders to include the wide bandwidth of a (then monochromatic) television video signal. At the time, kinescope recordings were made by photographing a TV picture tube on 16-mm movie film. Mullin, by then employed by Crosby Enterprises, developed an 11-track recorder which divided the video bandwidth into 10 equal portions. The first to be demonstrated, the recorder failed to achieve acceptance by broadcasters. The recorder was modified to serve as an instrumentation recorder and, along with the Crosby laboratories, was sold to the Minnesota Mining and Manufacturing Company to seed a line of wideband data recorders.

The Radio Corporation of America (RCA) showed an experimental machine having four tracks, one for each of the three primary colors and one for sound and synchronization. Its effort and a similar one by the British Broadcasting Corporation (BBC) failed for lack of market support.

Ginsburg, then employed by Poniatoff, developed the first practical videotape recorder. It used 2-in-wide tape and a rotating drum with four heads spaced 90 degrees apart around its periphery. One television picture required 32 traverses across the width of the tape. Further developed over 25 years, the technology was expanded to adapt to color television, stereo audio, longer playing time, and automated editing methods. Given the name *quadruplex*, the technology was extended to the recording of digitized video. A quadruplex digital TV recorder was demonstrated in 1976 but was not commercialized.

Helical-scan recording eventually replaced the quadruplex method. Long diagonal tracks are recorded at a shallow angle across 1-in-wide (or smaller) tape. Each track contains one television field. Less expensive to operate and maintain than quadruplex recorders, helical-scan recorders were capable of visual “tricks,” for example, still and slow motion display.

A television recorder must accommodate the associated sound. In both technologies, sound is recorded longitudinally, as in audio recorders. The audio tracks are located at or near the edges of the tape, the area most difficult for the rotating video heads to contact reliably.

The use of audio FM carriers, written by the video heads, was borrowed from home video technology for use in 1/2-in professional recording formats. This method offered excellent performance but was not amenable to editing audio separately from video, nor could it easily offer more than two channels.

As early as 1950, multichannel data recorders became available. They offered a wide range of speeds to provide time-base expansion and contraction, and bandwidths to 4 MHz per track, with tape speeds to 240 in/s. Adapted for data recording, rotary-head recorders achieved data rates of 500 Mbits/s. All rotary-head machines record at least one track along the length of the tape.

Audio recorders for the home, introduced in the early 1950s, and the prerecorded tapes provided for them were offered as long-life replacements for disks. These fell victim to the development of small lightweight recorders in which a narrow tape and its reels were housed in a small cassette. The ease of handling brought commercial success. Small battery-powered playback machines, having counter-rotating flywheels to cancel the angular acceleration induced by walking or running, soon became part of the street scene.

The insulation of the public from the mechanical niceties of preparing a reel of tape for use was an essential element in the introduction of video recorders into the home, all of which now use cassette tape. At first, television audio recording used the conventional longitudinal method, with limited performance. By 1983 two audio channels were impressed on frequency-modulated carriers and recorded along with the video by using the video record head. The audio performance of these home systems rivaled or exceeded the best of the professional analog recorders of the time.

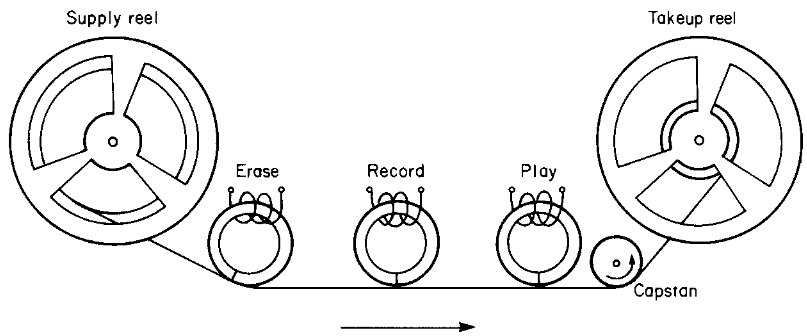

Figure 6.1.1 Essential elements of a tape recorder.

6.1.1b Basic System Components

The essential elements of a magnetic recorder are shown in Figure 6.1.1. A supply reel holds unused tape. A takeup reel collects used tape. A capstan establishes a constant linear tape speed. These mechanical elements combine to move the tape past the following:

- An erase head (optional). This is not a necessary element but is convenient. If it is not used, the tape must be erased elsewhere, usually on the reel in a device designed for bulk erasure.
- A record head (mandatory). The magnetic particles on the tape are influenced by the signal current in the record head as they pass by its gap. A bias signal is added which is either subsonic (dc) or supersonic (ac). It is important to remember that the addition of bias is a simple linear mix, and no modulation takes place.
- A reproduce head (the record head can be used after rewinding). The magnetized particles on the tape have fields which can link with the metal structure of the head and thereby induce a voltage in its winding.

6.1.2 General Recording and Reproduction Theory

If the signal current in the record head is directly proportional to the input signal, the recording is a *direct recording*. Almost all analog audio recorders use direct recording. If the record current is a frequency-modulated carrier on which the input signal is impressed, the recorder uses the FM method. Seldom employed for audio recording, FM recording is useful when the low-frequency response must be extended to zero or when the tape speed is too slow to support adequate frequency response, as in home video recorders. In this case, one or more FM carriers are recorded by the rotating video heads.

If the record current is a series of binary pulses whose repetition time varies according to the input signal, the recording method is called *pulse-position modulation*. This is not a digital recording in the usual sense but rather a form of phase modulation analytically similar to FM.

If the record current is a series of binary bits or a carrier modulated by binary bits, the method is called *pulse-code modulation* (PCM). In PCM, the input signal is sampled at a uniform rate that is greater than twice the input frequency range. Each sample is converted to a binary number, typically using 16 bits or more. The binary numbers are recorded, then later reproduced and converted to analog voltages.

In direct recording, the magnitude of the remanent magnetism left on the tape is a function of the input signal. In all other methods, it is constant, and the data are stored in the form of time variations or numeric values. Also, all other methods record at or near the maximum magnetic field that the tape can sustain. A strong constant recording field causes considerable (or by design, complete) erasure of previous recordings.

Some systems, therefore, need no erase head. All audio direct recorders, aside from toys, have an erase head.

6.1.2a Physical and Magnetic Relations

The maximum signal which can be recovered by a reproduce head is a function of many physical, electrical, and magnetic parameters. Some of these are defined in the following short glossary:

wavelength The distance along the tape, in the direction of tape motion, which is occupied by one cycle of a recorded signal. It is given by $\lambda = u/f$, where λ = wavelength (any unit of length), u = tape speed (same unit per second), and f = frequency of recorded signal (Hz).

magnetomotive force (F) The magnetic analog of electrical voltage, often expressed in ampere-turns, the product of a current and the number of turns in a coil of wire through which the current flows.

magnetic field (H) The magnetomotive force per unit length, usually expressed in oersteds. The relation between oersteds and ampere-turns is

$$H = \frac{1000 \times A_t}{4\pi \times l}$$

where A_t = ampere-turns and l = length (meters).

flux density (B) The intensity of a magnetic field per unit of cross-sectional area. A magnetic analog of electrical current, flux density is usually expressed in gauss.

permeability The magnetic analog of electrical conductance. The permeability of air is taken as unity. The permeability of metals and alloys used in recording range from the low thousands to the tens of thousands. For a given magnetomotive force, the resulting flux density is proportional to permeability. Initial permeability (at low flux densities) is given by

$$\mu = 1 + \frac{B}{H}$$

Where:
μ = permeability (a ratio)

H = magnetizing field
B = resulting flux density

saturation The maximum flux density that a material can sustain. As an applied magnetomotive force is increased, the permeability diminishes, until, at saturation, the permeability is unity and the flux density fails to increase further. In general, materials with high permeability have low saturation. It is important to select record-head materials, for example, which do not saturate at a lower level than the tape material. The efficiency of reproduce heads is maximized by choosing materials of the highest permeability.

remanence The ability of a magnetic material to retain magnetism after a magnetomotive force has been removed. Permanent magnets and recording media are selected for high remanence. Record and reproduce heads, shields, and transformer cores are chosen for high permeability and low remanence.

coercivity The measure of the magnetomotive force required to demagnetize a previously saturated remanent material.

squareness ratio The ratio of the saturation flux density to the remanent flux. High squareness ratio is a desirable property of recording media.

Weber A unit of flux. An ac magnetic field of 1 Wb at a frequency of 1 Hz, if linked with one turn of wire, will induce 1 V. Recording levels are typically expressed in terms of nanowebers per meter of track width.

6.1.2b Basic Direct Recording and Reproduction

With the addition of ac bias, the remanent magnetism remaining on the tape is a reasonably linear function of the signal current in the record head.

The maximum voltage available at the reproduce-head terminals is directly proportional to the track width, the remanent magnetism of the tape material, the rate of change of magnetism (and therefore, frequency), and the number of turns of wire on the head assembly. The basic expression is

$$e = KN\frac{d\phi}{dt} \tag{6.1.1}$$

Where:
e = instantaneous peak induced voltage
$d\phi$ = rate of change of induced flux
N = number of turns
$d t$ = rate of change of time
K = scale factor, representing all other effects

K is influenced mostly by losses related to short wavelengths.

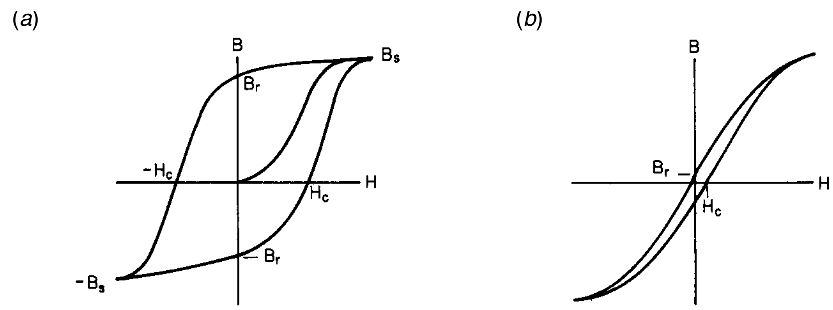

Figure 6.1.2 Hysteresis curves: (*a*) a hard material, (*b*) a soft material.

6.1.3 Magnetization

Almost all the magnetic properties of materials used in audio recording stem from the axial spins of the third shell of orbiting electrons of the atom. The electrical charge of the electron rotates, generating a current, which in turn generates a magnetic field. In nonmagnetic materials, electrons occur in pairs having opposing spin, canceling the magnetic effect. Iron, in particular, is heavily unbalanced, and nickel and chromium also exhibit magnetism. Compounds and alloys of these are useful in tape recorders. Applications include motors, transformers, loudspeakers, heads, tape, and shields.

The crystalline structure of magnetic materials includes groupings of millions of atoms whose spin axes are aligned. Each group is called a *domain* and in effect is a tiny saturated magnet. The direction of magnetization can be reversed by the application of a strong opposing field. In demagnetized materials, the direction of magnetization of the domains is randomly distributed, resulting in a net sum of zero.

6.1.3a Hard and Soft Materials

Figure 6.1.2*a* illustrates a hysteresis curve of a remanent or hard magnetic material; i.e., one which is difficult to demagnetize and therefore is useful for permanent magnets and recording media. Figure 6.1.2*b* is a curve representative of a “soft,” easy-to-demagnetize material useful for transformers, heads, and shields.

In Figure 6.1.2*b* the curve of initial magnetization shows the result of increasing an applied field on a demagnetized material. Around the origin, the effect is reversible; i.e., upon removal, the material will return to its random state. As the field is increased, the flux density increases as more domains switch direction in response to the applied field.

At point B_s , not only have all domains switched, but those whose spin axes are aiding but are not perfectly aligned have their axes deflected to line up with the applied field. This is known as *saturation*. If the magnetizing field H is removed, the flux density decreases somewhat as the domains that were not perfectly aligned revert to their undeflected axis angle; i.e., not 100 percent aiding but not opposing either. This is shown in Figure 6.1.2 as point B_r.

The ideal tape particle is a single domain with its spin axis aligned with the lengthwise dimension of the tape. If these alignments were perfect, B_r would equal B_s and the hysteresis loop would approach a square. The ratio B_r / B_s, called the *squareness ratio*, is therefore a measure of the success in aligning tape particles during manufacture.

If the applied field is increased in the opposite direction, more domains switch again until point $-H_c$ is reached. Here, half of the domains have switched and half have not, resulting in a net flux density of 0. The force required to reach this point in a previously saturated material is the measure of the coercivity of the material.

6.1.3b Bias

Figure 6.1.3*a* is a plot of remanent flux versus an applied field, showing the effect of dc bias. The curve is not symmetric about the bias point; therefore, the spectrum of distortion components of a recorded sine wave will contain even as well as odd multiples of the fundamental frequency. A tape recorded without audio still will generate a signal as the tape moves over the reproduce head. Surface roughness and a coating thickness that varies at audio rates will directly modulate the field in the reproduce head, generating noise.

Figure 6.1.3*b* illustrates ac bias. The peak-to-peak amplitude of the supersonic signal is constant and is about twice the dc value. The bias signal can be thought of as a high-frequency switching signal, magnetizing for half of the time in one direction and half in the other. The noise performance is vastly improved because the net average magnetization is 0. The sum of the shapes of the upper and lower portions of the curve is such that even-order-harmonic-distortion components of the audio signal cancel.

6.1.3c Erasure

Figure 6.1.4 shows the hysteresis loops traced as a remanent material is exposed to a large, slowly decreasing magnetic field. The net result as the ac field approaches 0 is to randomize the domains, leaving the material demagnetized. The high-frequency excitation of an erase head is constant, and the diminishing field effect is obtained as a given spot on the tape moves away from the gap of the head. The choice of frequency and tape speed must cause the tape to experience several field reversals.

6.1.4 Magnetic Recording Materials

The active component of magnetic tape is the first of four components:

- The magnetic material itself.
- A binder, or glue, which surrounds the magnetic material and holds it to a plastic support.
- A plastic support, usually polyethylene terephthalate, also known as polyester. After coating, if slit into strips, it becomes tape.
- A conductive back coating is applied if the application includes severe winding-speed requirements.

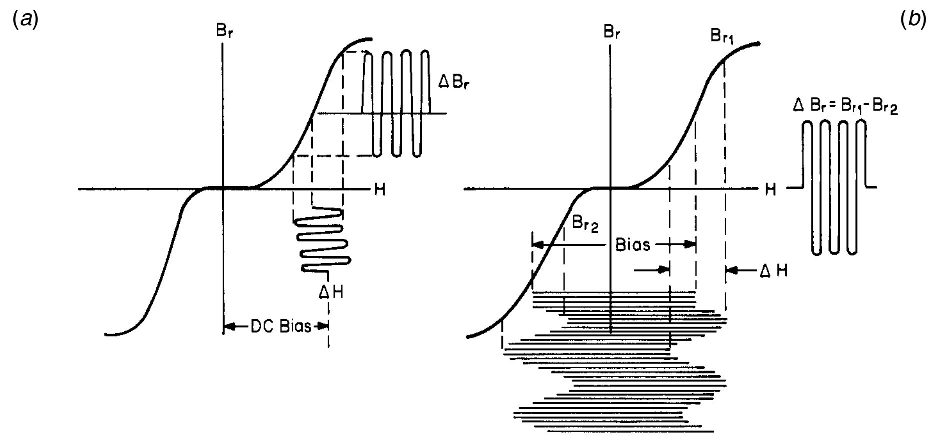

Figure 6.1.3 Bias for audio recording applications: (*a*) dc bias, (*b*) ac bias.

6.1.4a Iron Oxide

Having a coercivity of 300 to 360 Oe, gamma ferric oxide is the most widely used recording material. The first step in its preparation is the precipitation of seeds of geothite [alpha FeO (OH)], from scrap iron dissolved in sulfuric acid, or of lepidocrocite [gamma FeO (OH)], produced from ferrous chloride.

After further growth the seeds are dehydrated to hematite (alpha Fe_2O_3), then reduced to magnetite (Fe_3O_4). It is then oxidized to maghemite (gamma Fe_2O_3), which not only is magnetic but has the desired acicular (rod-shaped) form with an aspect ratio of 5 or 10: 1. The length of the particles is 0.2 to 1.0 μm.

6.1.4b Cobalt-Doped Iron Oxide

Having a coercivity of 500 to 1200 Oe, the preferred preparation causes cobalt ions to be adsorbed upon the surface of gamma ferric oxide particles as an epitaxial layer. This is one form of high-bias tape.

6.1.4c Chromium Dioxide

Offering coercivities of 450 to 650 Oe, this material provides a slightly higher saturation magnetization, 80 to 85 emu/g, compared with 70 to 75 emu/g for gamma ferric oxide. It has high acicularity and lacks voids and dendrites. It has a low curie temperature, making it a likely candidate for contact duplication of video tapes or other short-wavelength recordings.

Chromium dioxide is abrasive, tending to reduce head life. It is less stable chemically than iron oxide. At extremes of temperature and humidity, it can degrade to nonmagnetic compounds of chromium. Tapes made with cobalt or chromium oxides yield output levels of 5 to 7 dB greater than gamma ferric oxide of the same coating thickness. Chromium dioxide does have a

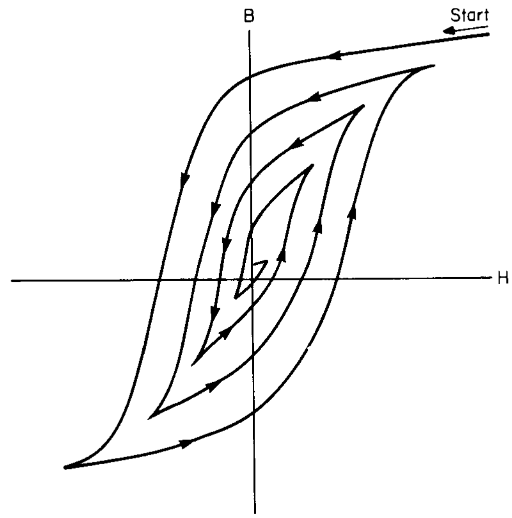

Figure 6.1.4 Erasure by a diminishing ac field.

problem in respect to disposal. In many countries, chromium and its compounds are subject to special treatment when discarded.

6.1.4d Iron Particle

Tapes made from dispersions of finely powdered metallic iron particles are capable of 10- to 12-dB greater signal output than gamma ferric oxide tapes. These tapes have high saturation magnetization (150 to 200 emu/g), a retentivity of 2000 to 3000 G, and a coercivity of 1000 to 1500 Oe.

Several processes generate metal particles. One is the reduction of iron oxide in hydrogen. Another is the reduction of ferrous salt solutions with borohydrides.

Metal particles, being very small, take longer to disperse, a disadvantage in manufacture. When dry, iron particles are highly reactive in air and present a processing hazard. Corrosion at elevated temperatures and humidity is also a problem.

6.1.5 Bibliography

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Chapter

6.2

Analog Tape Recording

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6.2.1 Introduction

Within the audio passband, frequency-dependent recording losses are generally negligible, consisting mainly of changes in the permeability of reproduce-head cores versus frequency. Most reproduce losses are directly related to the recorded wavelength, which, at a given tape speed, can be expressed in terms of frequency.

In an imaginary perfect reproduce system, the output from the reproduce head would double with each doubling of frequency. Various effects cause the output at high frequencies to be less than ideal, including:

- Thickness loss
- Spacing loss
- Azimuth loss
- Gap loss

6.2.1a Thickness Loss

The particles at the surface of the tape which have reversals of magnetic direction link with the reproduce-head pole pieces and generate a signal. Their neighboring particles within the depth of the coating have their fields partly canceled by other nearby particles of opposite magnetization which are also distant from the pole pieces. The influence of a given particle on the output diminishes at 55 dB per wavelength of separation from the head. The thickness loss in decibels is

$$20\log\frac{1-\exp(-2\pi d/\lambda)}{2\pi d/\lambda} \qquad (6.2.1)$$

where d = depth of recording and λ = wavelength, in same units.

6.2.1b Spacing Loss

The surface of the tape is not perfectly flat. If it was, it would adhere to points of sliding contact with disastrous results. Surface particles, therefore, vary in their distance from the pole pieces. The loss due to this average separation in decibels is

$$20\log\exp(-2\pi a/\lambda) \tag{6.2.2}$$

where a = average spacing of surface particles and λ = wavelength, in same units.

6.2.1c Azimuth Loss

If the angle of the reproduce gap with respect to the direction of tape motion is different from the angle of the recording gap, there is an additional loss. The loss in decibels is

$$20\log\left\{\frac{\left(\sin\frac{W\tan\theta}{\lambda}\right)}{\left(\frac{W\tan\theta}{\lambda}\right)}\right\} \tag{6.2.3}$$

Where:
θ = differential angle
W = track width
λ = wavelength, in same units as width

This loss can be severe, especially with wide tracks. Head assemblies are usually provided with means to adjust the verticality of the gap. Typically, a reference tape made by a certified supplier is reproduced and the azimuth angle of the reproduce head adjusted for maximum output while reproducing a high frequency.

6.2.1d Gap Loss

When the recorded wavelength is equal to the gap length, the summation of the influence of the magnetic particles within the gap is zero, and there is a null in response. For wavelengths longer than the gap, the loss can be expressed as

$$20\log\frac{\sin\left(\frac{1.11\pi g}{\lambda}\right)}{\left(\frac{1.1\pi g}{\lambda}\right)} \tag{6.2.4}$$

where g = optically determined gap length and λ = wavelength, in same units.

Gap loss is typically less than 6 dB. Compensation for this loss is often provided by resonating the head inductance with cable capacitance at a frequency well above the system's upper band limit. Alternatively, a dedicated circuit may be used to provide a rising response to cancel the gap loss.

6.2.2 Long-Wavelength Effects

Except for the particular case of a circular head structure [1] at those low frequencies that produce wavelengths which approach the width of the head structure, undulations in response occur, including reinforcement. These are known as *head bumps*. Making pole pieces of the head structure very wide tends to move the undulations below the audio spectrum. This, however, makes the head a more efficient transformer, therefore increasing crosstalk with adjacent heads. There is no easy electronic compensation for head bumps; thus, there is a range of tradeoffs between crosstalk and low-frequency response.

6.2.2a Equalization

Equalization, the process of correcting deviations from uniform frequency response, is distributed between the record and reproduce circuits. In general, losses attributable to the reproduce process are corrected in the reproduce circuits, and vice versa.

The major loss during reproducing is inversely proportional to wavelength for wavelengths which are short compared with the tape coating thickness. If we assume a recording having uniform record current with frequency and no other losses, the system response is dominated by the thickness loss. Thickness loss has been found to approximate the response of a simple resistance-capacitance (RC) low-pass circuit. The reproduce system must therefore have an inverse response, rising with frequency.

On the basis of measurements made on typical tape samples, a standard reproduce curve is selected and promulgated by various standards organizations to effect tape interchange among similar machines. The response at high frequencies is expressed in terms of an RC product, or time constant. The reproduce-system response is given by Equation (6.2.5). Values range from 15 to 120 μs. Thicker tape coatings and slower tape speeds require the larger values.

$$\text{Gain (dB)} = 10\ \log[1 + (2\pi f R_1 C_1)^2] \qquad (6.2.5)$$

In some systems, the low frequencies are boosted during recording and attenuated during playback to reduce ac hum and other low-frequency noise. The associated inverse reproduce response is given by

$$\text{Gain (dB)} = 10\ \log\left[1 + \frac{1}{(2\pi f R_2 C_2)^2}\right]^{-1} \qquad (6.2.6)$$

A typical RC value is 3180 μs. Where RC is nonzero, there is a frequency, usually between 400 and 1000 Hz, at which the influences of the two equalizations are equal and their sum is

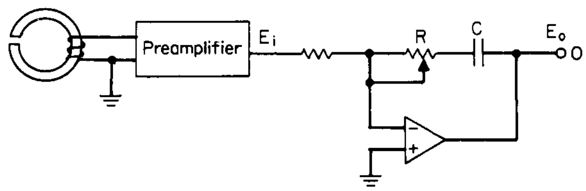

Figure 6.2.1 Elements of a reproduce equalizer.

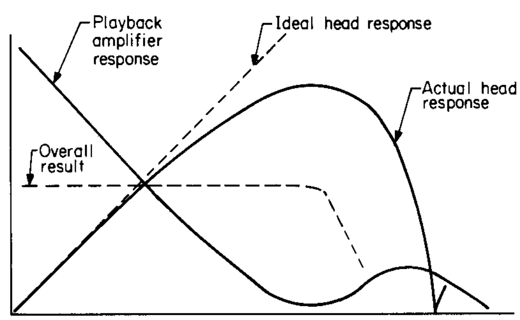

Figure 6.2.2 Complementary responses of the reproduce system and equalization.

minimum. The frequency, given by Equation (6.2.7), is useful as a test frequency and is obtained by equating Equations (6.2.5) and (6.2.6) and solving for B.

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{R_1C_1R_2C_2}} \tag{6.2.7}$$

Figure 6.2.1 highlights the essential elements of a reproduce equalizer. At low frequencies the impedance of the feedback path is predominantly capacitive, and the response of the amplifier falls at 6 dB per octave, compensating for the rising frequency response of the head. At high frequencies, the response of the amplifier is determined by the value of R and becomes flat. Figure 6.2.2 illustrates how the response of the head-tape interface and the reproduce equalizer complement each other.

Adjustment of reproduce equalization circuits may be accomplished in two ways. First, a reference tape prepared under laboratory conditions and containing several frequencies is reproduced and circuits adjusted for the most uniform response. Some reference, or alignment, tapes are recorded full-width to avoid errors due to imperfect vertical positioning of heads relative to the recorded tracks. Equation (6.2.8) in conjunction with Figure 6.2.3*a* will calculate the rise in response due to fringing fields from the parts of the tape that are not ordinarily recorded upon. Equation (6.2.8) is sufficiently accurate to correct for the rise in output at frequencies usually

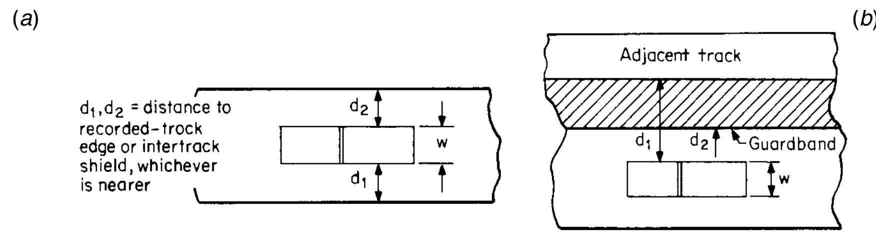

Figure 6.2.3 Dimensions for (*a*) fringing-gain calculation and (*b*) crosstalk calculation.

employed to set the playback-system gain. At longer wavelengths, the rise is more pronounced and accuracy suffers.

$$\text{Fringing gain (db)} = 20\ \log\left[1 + \frac{2 - \exp(-kd_1) - \exp(-kd_2)}{2kW}\right] \qquad (6.2.8)$$

where $k = \pi$ frequency/velocity and W = head width.

Second, the desired reproduce response is calculated from Equation (6.2.5) and the inverse of Equation (6.2.4). The head is excited by a small coil of wire driven by a test oscillator. The reproduce circuits are adjusted until the obtained response is most nearly equal to the calculated response. Alternatively, a circuit having a response which is the inverse of the calculated response can be interposed between the test oscillator and the coupling loop. The reproduce circuitry is then adjusted for flat response.

6.2.2b Noise

Noise is anything that appears at the output that was not present at the input and is not a function of any of the input signals. Crosstalk and distortion products are not noise. Coherent interference may be injected into the reproduce path either magnetically (coupled into the reproduce head) or electrically (introduced into the reproduce circuitry). The usual source of coherent interference is the ac power supply. Radiation from the power transformer into the reproduce head and coupling of the third harmonic of the power line frequency into high-gain circuitry are typical sources. Encasement of the power transformer in a surrounding enclosure of magnetic material is highly recommended. AC motors may be shielded and/or rotationally oriented for minimum field radiation in the direction of the reproduce head. The circuit path for ac motors should never share any wiring or other element of the transport structure with the signal circuit.

Analog audio recorders in a television environment frequently experience interference from the magnetic fields originating in the scanning yokes of television monitors. The vertical scanning waveform is rich in harmonics which lie within the audio passband and is therefore difficult to cancel. Only the fundamental of the horizontal scanning frequency is of interest. Shielding of television monitors is difficult. The viewing end of the monitor cannot be obscured, and shielding around the yoke tends to remove too much energy from the scanning yoke.

Random Noise

Unrelated to the recorded signal, random noise stems from several sources. The random distribution of magnetic particles in the tape is, ideally, the major source.

Electronic noise includes the thermal noise of the resistive component of the head windings and the semiconductor junction noise in the preamplifier. If electronic noise is kept at least 10 dB below tape noise, its contribution to the overall signal-to-noise (S/R) ratio will be limited to 1 dB or less. Electronic noise in the preamplifier can be minimized by the following design steps:

- Locate the preamplifier as closely as possible to the reproduce head to minimize the capacitance of the wiring to the head.
- Choose a head inductance as high as possible without having the inductance and associated capacitance resonate too close to the upper band edge. Resonance at two or three times the upper and edge is reasonable. This technique maximizes the number of turns of wire on the head winding and therefore the induced voltage.
- Careful selection of a small-signal transistor. It should have low shot (1/*F*) noise at low frequencies. Calculate the source impedance of the head at 6.3 kHz, approximately the frequency of maximum sensitivity of the human ear. Choose the current through the transistor to produce the minimum noise figure at the calculated source impedance. Avoid the use of balanced (push-pull) designs which involve the use of two active junctions. Two junctions make more noise than one.

The playback noise from a tape subjected to ac bias current, but no signal current, is usually greater than that from a tape subjected to nothing. This effect can be minimized but not eliminated.

6.2.2c Reproduced Crosstalk

The coupling of a magnetic track into a neighboring reproduce head is given by Equation (6.2.9) in conjunction with Figure 6.2.3*b*.

$$\text{Crosstalk (dB)} = 20\ \log\left[\frac{\exp(-kd_1) - \exp(-kd_2)}{2kW}\right] \qquad (6.2.9)$$

where $k = \pi$ frequency/velocity and W = head width.

Equation (6.2.9) assumes no intertrack shield. Another source of intertrack crosstalk is the magnetic coupling between the two head structures, similar to the relation between the primary and the secondary of a transformer. The combination of these two effects is a wildly gyrating function at low frequencies.

A degree of cancellation of intertrack crosstalk can be effected by injecting a small fraction of the reproduced voltage of a channel into its neighboring ones in antiphase. The cancellation is most effective in the middle range of frequencies.

6.2.2d Circuit Design Considerations

The establishment of a point in an electrical system that may be considered as reference zero is not trivial and is the subject of many books and learned papers. Audio-recorder designs tend to establish a reference ground at the reproduce preamplifier. Another approach is to declare reference ground as the point of attachment of the power supply filter capacitors.

In all cases, the interference between circuits caused by currents developing voltages across ground wires can be minimized by reducing the impedance of those wires. Ground pins on plug-in circuit boards should be numerous. Ground interconnections should be massive, consisting of either large-cross-sectional-area conductors or multiple wires of equivalent conductance.

With larger systems having longer interconnections, the use of balanced transmission on two wires for each signal path is highly recommended, as it can bring significant reductions in conductive crosstalk.

High-impedance circuits can suffer interference from nearby signals by capacitive coupling. This form of interference can be diminished through the use of an electrostatic shield, one that is conductive but not magnetic. Examples include aluminum shield cans, braided or wrapped shields around wires, and metal enclosures.

Low-impedance circuits, especially the reproduce head and its wiring, can suffer from interfering ac magnetic fields. Notable sources of interference include power supply transformers and reel and capstan motors.

Sometimes it is necessary to attenuate the interference at the source; i.e., to enclose a motor in a can made of magnetic material. The greatest source attenuation is achieved by encasing the offending item in an inner shield of material which has moderate permeability but is capable of sustaining fairly strong fields without saturating. The outer shield is then formed of a material with very high permeability. Such materials tend to saturate even in moderate fields, but the inner shield attenuates the field to a tolerable level.

Shielding of the reproduce head is difficult. It is obviously not possible to fully enclose the head. The maximum practical shielding is obtained by mounting the head in a cup made of a sandwich of Mumetal separated by copper. (See Figure 6.2.4.) A cap made of the same material is formed to cover the cup. Small slots are cut in the cup to allow passage of the tape. The cap is retracted to thread the tape but pressed against the cup in normal operation.

The wiring between the reproduce heads and the associated preamplifiers is especially critical. If the distance is more than a few inches, it would be wise to encase the wires in a tubular magnetic (and electrostatic) shield. In any event the head wires should be tightly twisted.

6.2.3 Audio Recording Process

For virtually all applications, the audio signal to be recorded is mixed with a supersonic single-frequency ac signal prior to being coupled to the record head. It is important to understand that the addition of bias is strictly linear. No modulation is intended, and no multiplicative products of modulation are needed or desired.

Figure 6.2.5 shows how the spectrum of noise due to the granularity of the magnetic particles in the surface of the tape is distributed around the bias frequency. The lower skirt of the spectrum invades the audio spectrum. This explains the commonly observed difference between noise measured from virgin bulk-erased tape and noise measured from tape which has been biased (and recorded) with zero signal. Increasing the bias frequency will reduce the magnitude of

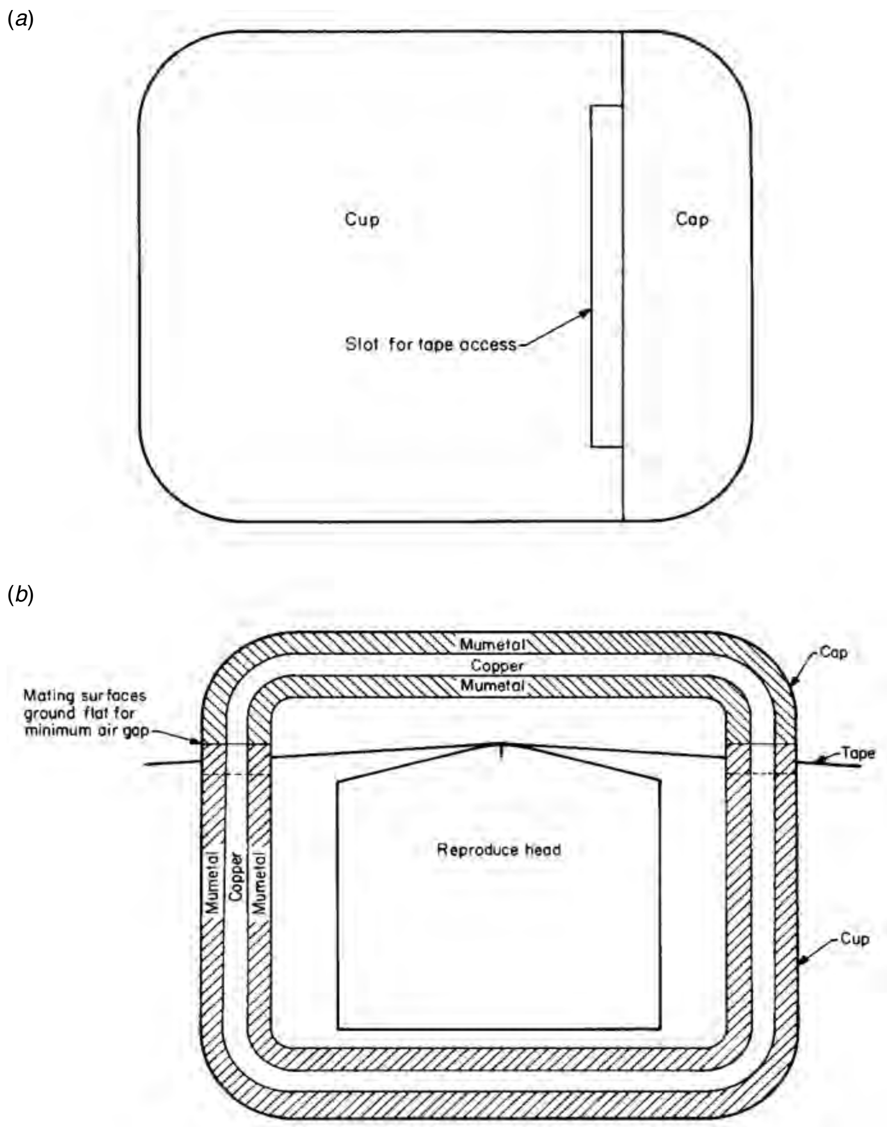

Figure 6.2.4 High-quality head shield: (*a*) side view, (*b*) top cross section.

biased noise slightly. Obtaining adequate bias and erase currents at reasonably low voltages is a problem at high bias frequencies.

The erase frequency is usually equal to the bias frequency. Sometimes it is less. If so, it should be an odd submultiple of the bias frequency.

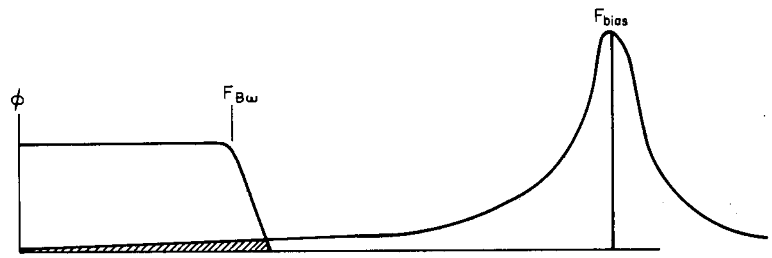

Figure 6.2.5 Intrusion of the bias noise spectrum.

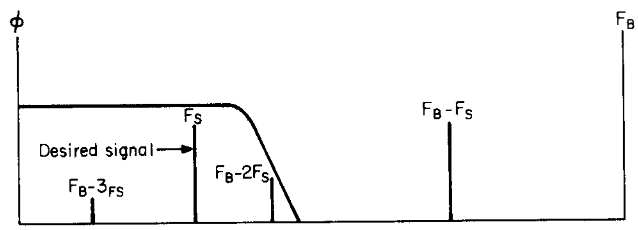

Figure 6.2.6 Alias interference due to large distortion products.

If too low a bias frequency is chosen, then the recording of high-amplitude, high-frequency signals will, in a process akin to phase modulation, generate a family of sidebands spaced at *N* times the signal frequency above and below the bias frequency, where *N* is an integer. Figure 6.2.6 illustrates how these artifacts can intrude into the audio passband. The effect is easily heard by recording a high-amplitude sine wave of rising frequency and listening for descending tones upon playback. A bias frequency at least 7 times but not more than about 20 times the highest frequency to be recorded is reasonable.

Figure 6.2.7 shows the relation between bias amplitude and the remanent audio signal. Note that the high-frequency, short-wavelength signal reaches a maximum at a lower bias current than the long-wavelength signal. The bias field is strongest at the surface of the tape and diminishes as it penetrates the thickness of the tape coating. The particles contributing to low-frequency output include some near the surface, which are overbiased, and some within the depth of the recording, which are underbiased. The particles responsible for high frequency response are confined to the surface and are all overbiased.

Operationally, bias current is adjusted by recording a moderately high-frequency signal, producing a wavelength which is short compared with the thickness of the tape coating. The bias amplitude is slowly increased until the audio output reaches a maximum, then decreases by an amount prescribed by the manufacturer. This method is adequately sensitive and is designed to result in a minimization of distortion at low and medium frequencies. In the particular case of thick tape coatings and record heads having a gap length approaching the coating thickness, a sharp reduction in distortion can be obtained by careful adjustment of bias amplitude.

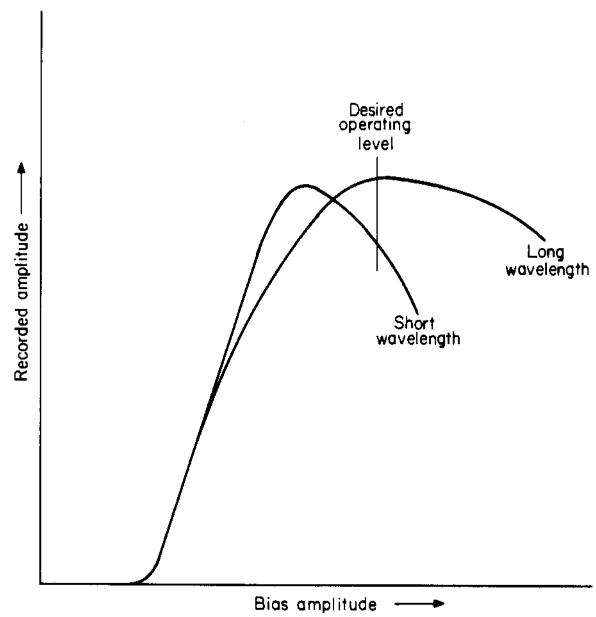

Figure 6.2.7 Influence of bias amplitude.

Some recorders which have separate record and playback heads offer automatic bias adjustment. Two built-in test oscillators, one at a low frequency and the other near the upper band edge, are mixed in a known ratio and injected into the record path. A playback circuit examines the ratio between the reproduced tones and adjusts the bias amplitude until the correct ratio is achieved. The adjustment value is stored in nonvolatile memory.

6.2.3a Measurement of Record Amplitude

The choice of a “normal” recording level is a careful tradeoff between noise and distortion. A tape recorded consistently at too high a level of magnetization will exhibit excessive and perhaps noticeable odd-order harmonic distortion. If recorded at too low a level, the S/N will be degraded. A typical normal analog record level is 8 or 9 dB below the level resulting in 3 percent third-harmonic distortion.

Two methods of signal-level measurement are used, sometimes together. The volume-unit (VU) meter, standardized in the U.S., indicates decibels above 1 mW across a 600-Ω line. The ballistics of the meter are closely specified and controlled to obtain repeatable results. The meter is limited in its ability to respond mechanically to very short signal peaks. Use of this meter to adjust loudness dynamically results in occasional bursts of high distortion depending on the program content but in a relatively constant S/R.

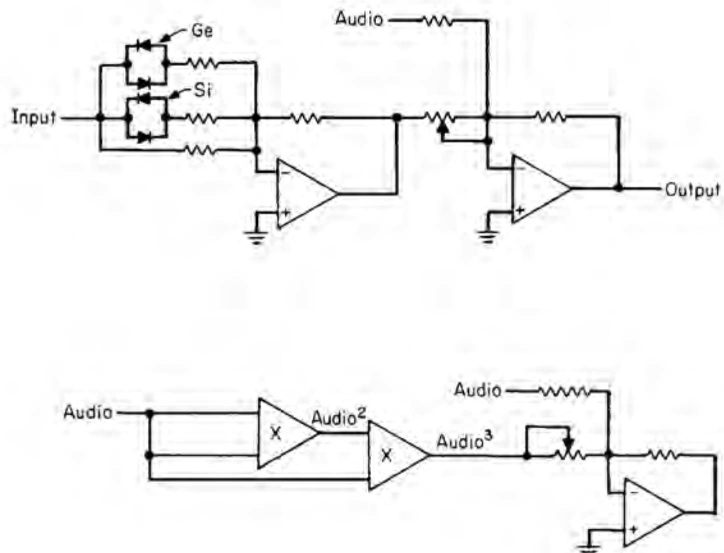

Figure 6.2.8 Common circuits for amplitude predistortion; X = four-quadrant multiplier.

In Europe and on many consumer products, metering of the record level is done with a peak-reading instrument consisting of a fast-charge-slow-discharge circuit driving either a conventional meter movement or a linear array of light-emitting diodes. This display method indicates instantaneous peaks of amplitude long enough for one to see and react to them. Use of peak-reading instruments tends to produce a constant maximum distortion level and an S/R ratio which varies according to the program content.

6.2.3b Distortion Reduction

The only distortion products which should be detectable at the output of a properly designed and maintained tape recorder are the odd-order harmonics of the signal frequency. The predominant harmonic is the third. The absolute amplitude of the harmonic is closely proportional to the cube of the amplitude of the recorded signal. The sign of the harmonic is such that the peak amplitude of the signal is reduced. The limiting case is that of a totally overdriven system with a sine-wave input and a square-wave output.

One technique to make the system more linear is to create, in the recording process, odd-order distortion of the opposite sign and add it to the signal to be recorded, thus canceling in advance the effects of the inherent distortion produced by the magnetic medium. Called *predistortion*, this technique is presented in Figure 6.2.8, which shows ways to approximate the desired function.

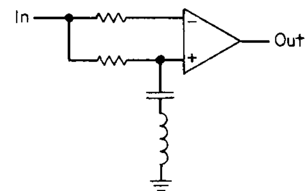

Figure 6.2.9 Second-order delay correction circuit.

The recording process also introduces *delay distortion*, the nonuniform time response to the various frequencies in the input spectrum, brought about by the interaction of the longitudinal and vertical components of the recording field. This effect may be compensated for by introducing delay distortion of the opposite sense. Figure 6.2.9 shows a second-order all-pass circuit which will partially compensate for the delay distortion. As in the case of amplitude predistortion, there is no reason other than economics that delay distortion correction must be accomplished in the record process. The easiest but not necessarily best way to establish circuit values in a phase predistorter is to determine experimentally the values which result in the best square-wave response at midrange frequencies; i.e., 500 to 2000 Hz.

6.2.3c Record Equalization

Most recorders have at least one adjustment in the record path to set the frequency response at the upper end of the spectrum. In simple consumer recorders, a single RC variable boost usually suffices. Professional mastering recorders have as many as four, including adjustment of low-frequency response. Record equalization is always set after setting reproduce response and after setting bias amplitude in order to achieve the flattest overall system response.

6.2.3d Record Crosstalk

The degree to which a record signal is also recorded, in part, on an adjacent track depends on whether the adjacent track was also being recorded upon at the time. If a bias field is present on the adjacent track, that track is most sensitive to the presence of leakage flux from its neighbor. Two paths exist for introducing one signal path into another. The first magnetic path extends from the face of the record head into the face of the neighbor. The other path is the transformer coupling between the two heads within the structure of the head assembly. Transformer coupling can be greatly reduced by the introduction of interchannel magnetic shields.

Record crosstalk may be partially canceled by injecting into each neighboring channel's record path a fraction of the record signal in antiphase. The cancellation signal is frequently passed through a circuit which varies its amplitude and phase as a function of frequency. Generally the adjustments are critical, and generally the cancellation is effective only over the midrange frequencies, roughly 500 to 5000 Hz.

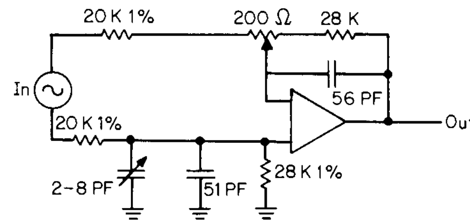

Figure 6.2.10 Differential-input amplifier circuit.

6.2.3e Circuit Design

Analog consumer recorders typically have rather simple input circuits. The input cable is usually a single shielded conductor with the shield connected to ground. While this is adequate when the signal source is a meter or two away, professional recorders may be operated with sources which are tens of meters removed. To avoid introducing interfering signals due to currents in the ground paths, professional recorders usually have a balanced input with bipolar signals symmetrical about ground. The input device is sometimes a transformer, but better rejection of common-mode interference can be gained with an operational amplifier with one or two adjustments to maximize common-mode rejection (CMR). Figure 6.2.10 shows a typical circuit. The potentiometer adjusts CMR at low frequencies, and the variable capacitor minimizes CMR at high frequencies.

Two methods of adding the bias signal to the audio are in common use; Figure 6.2.11 shows both. In one, the bias-generator output is added to the audio record-amplifier output by using passive components. In the other, the bias is added at the input to the record amplifier, which must be designed to have the bandwidth and output-amplitude capability to amplify the mixture without distortion.

The design of the bias source is critical. The bias current must be free of even-order distortion and must be spectrally pure. Even-order distortion will result in even-order distortion of the audio signal and in increased tape noise. Spectral impurity will result in increased modulation noise; i.e., noise which occurs only in the presence of a signal.

Additionally, in recorders used for editing, the bias and erase signals are turned on and off slowly to prevent clicks, pops, and thumps at the edit point. It is important that the bias and erase waveforms remain free of even-order distortion during the turn-on-turn-off period.

The following record controls may be found in record electronics, usually repeated for each channel:

- A user-adjustable front-panel record level control that compensates for the variation in level at the input terminals.
- Calibration control to adjust the sensitivity of the record level display device.
- Record equalization control to set the overall frequency response to maximum flatness.
- Bias amplitude. Cassette recorders and less expensive reel-to-reel machines often provide a single bias adjustment, with the different amplitudes required by different tape formulations being set by a resistive voltage divider using fixed components. Professional machines usually provide separate adjustments for each tape type and an adjustment for erase amplitude as well.

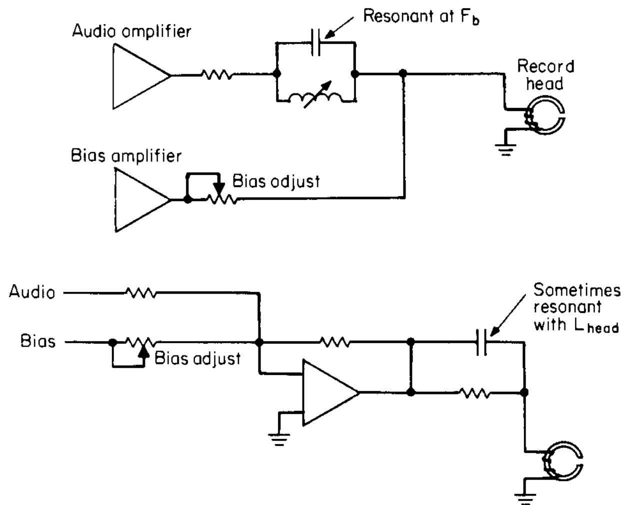

Figure 6.2.11 Two common bias-addition methods.

- If the recorder is equipped with one or more noise reduction circuits, there is usually a record calibration control which is set to produce a standard level at the input to the noise reduction circuit. Another record calibration control is used to establish the desired tape flux at the standard input level.

6.2.3f Editing

Where the tape is accessible, the end of one passage may be mechanically joined to the beginning of the next by cutting the two tapes at the appropriate points, abutting the two ends, and securing them with adhesive tape on the nonoxide side of the tape. The cutting is done in a jig with a groove equal to the width of the tape. The two tapes are put in the groove and overlapped. The cut is always made through both layers at once, assuring a precision fit. Usually, a diagonal cut is made to spread the effect of the splice over a period of time, producing a cross-fade of sorts between the two signals.

When the finality of a mechanical splice is too risky or when there is a multi-track recorder on which some tracks need editing and others must be retained, electronic editing is used. When the record command is issued, the erase current is ramped up over a period of 5 to 100 ms. Later, when the beginning of the erased tape reaches the record head, the bias current and audio signal are ramped up over a similar time. When recording is terminated, the procedure is reversed, with the erase being ramped down first. Figure 6.2.12 shows the timing and resulting effect. The on and off delays are different for bias and erase, different for ramping up and ramping down, and different for each tape speed. To avoid holes in the recording at either the start or the end of the edit, each of the delays is, in some machines, made adjustable.

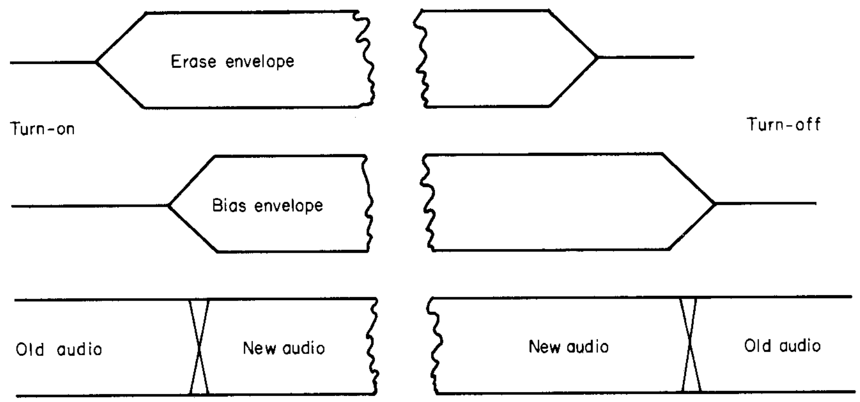

Figure 6.2.12 Erase and bias on-off timing.

In some applications, as when the sound in a movie being filmed is magnetically recorded, it is necessary to assure that the tape recorder plays back at precisely the same speed used during recording even when the tape has shrunk or stretched. An early method of doing this was to record a narrow track of a single reference frequency in the guard band between two tracks. The frequency was derived either from the ac power line, if the camera was equipped with a synchronous motor, or from an ac generator attached to the camera drive shaft. During playback, the reproduced reference signal was compared with the reference and the speed of the recorder controlled to cause their frequencies to be the same.

Early recorders used synchronous ac motors, and speed was controlled by driving the motor with a power amplifier driven with a variable-frequency oscillator. In more modern machines, the capstan is driven by a dc motor having a tachometer disk on one end of its shaft. Speed is controlled by comparing the tachometer frequency with a suitable variable-frequency generator. A typical nominal tachometer frequency is 9600 Hz. In both of the schemes outlined here, initial synchronism is achieved manually and maintained by the servo system thereafter.

A digitally encoded time and control code suitable for recording was developed under the auspices of the Society of Motion Picture and Television Engineers (SMPTE) [2]. The code is also supported by the European Broadcasting Union (EBU) [3]. Time is expressed, using two binary-coded decimal digits per 8-bit byte, as hours, minutes, seconds, and television or film frames and is iterated once each frame. A total of 80 binary bits are recorded per frame; 16 bits provide synchronism and direction sense, 32 are used to express time, and another 32 are available to the user for any purpose. This signal is very useful in a television environment and is employed in situations in which audio is recorded separately from video or the audio of a television program is to be separately manipulated before broadcast. The time code is recorded either on one track of a multichannel recorder or on a narrow track between two audio tracks

A *synchronizer* is either an external electronic device or a plug-in accessory circuit board to a recorder which compares time codes replayed from a master recorder and from a slave reproducer, and controls the capstan of the slave to maintain the difference between the two time codes at zero or some desired fixed offset. In this way, the slave, usually an audio reproducer, and the master, usually a video recorder, are kept in synchronism. Unlike earlier rate-only servos, synchronizers can both attain and maintain synchronism.

Editing systems which control numerous video and audio recorders and video and audio switchers and mixers have been devised and are in common usage. All make use of the SMPTE-EBU time code to determine the relative time position of video and audio program materials and to control the various machines presenting those materials.

The rehearsal of proposed edits, the accumulation of a list of edits within a program, and the generation of a master tape conforming to the *edit decision list* are typical features of these systems.

6.2.4 Mechanical Considerations

The essential elements which may be mounted on the frame are shown in Figure 6.2.13. If the elements are intended to be mounted vertically, as in an equipment rack, the mounting method must isolate planar irregularity of the rack from the frame. If vertical or horizontal mounting is intended, the bending of the frame due to the weight of the components mounted upon it must be calculated and determined to keep the plane of the mounting surfaces adequately flat. The frame, in its simplest form, is a sheet of rolled metal. In its most complex form, it is a casting with deep webs to increase stiffness.

In large recorders, some of the electronic elements may be mounted directly on the frame. These are mostly circuits which benefit from short wiring or which are electronic sensors of mechanical elements. Included are playback preamplifiers, motor-drive amplifiers, optical tachometer sensors, tension arm-deflection sensors, and solenoids which move some of the mechanical elements.

6.2.4a The Tape Path

The purpose of the elements shown in Figure 6.2.13 is to keep the tape under tension while moving it across the head assemblies. The supply reel, whether driven by a separate motor or by a friction clutch, supplies torque in the direction opposite to normal tape travel. In the play mode and the fast-forward mode, this maintains tape tension. In the rewind mode, it serves to accelerate the tape and the takeup reel, and return the tape to the supply reel. The takeup reel, in a like manner, supplies torque in the forward direction.

In friction-drive systems and those with ac motors, the torque applied to the reels is relatively constant, causing the tape tension to vary with the diameter of the tape pack. For this reason, the ratio between full and empty reel diameter is usually restricted to 2.5 or 3: 1.

In friction-driven reel systems and in separate-motor systems with unipolar motor-drive amplifiers, the torque is always in the direction shown. In larger recorders, especially those which handle large reels of wide tape, the motor-drive amplifiers are often bipolar. This allows the motor to aid in the acceleration of a reel rather than depend on the increased tension on the tape to do it alone. Quick response to rewind and fast-forward commands can thus be obtained while restricting tension transients in the tape. Tension transients are often the cause of tape cinching, shown in Figure 6.2.14. This occurs when the outside of the tape pack rotates in respect to the inner part.

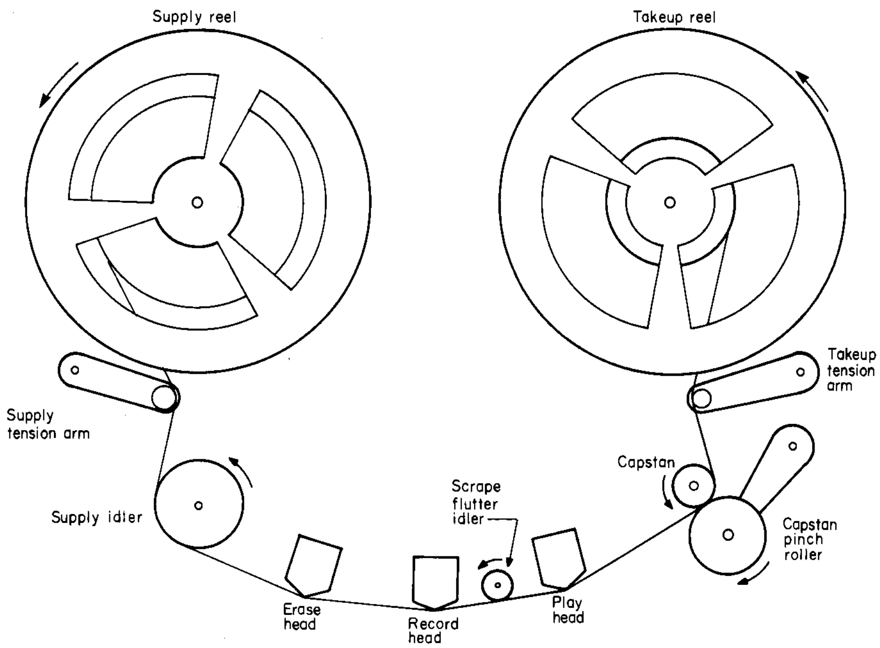

Figure 6.2.13 The essential elements of a tape transport.

The supply and takeup reels are usually supplied with frictional brakes even if these are used only in the event of power failure. Figure 6.2.15 shows how an active element, a solenoid, is used to hold the brakes off so that power failure will result in brakes on. The springs at each end of the brake band are unequal, resulting in the greater braking force being applied to the unwinding reel. This maintains tension even when the system stops in the absence of power.

The braking force is the product of the spring force and the capstan effect, a multiplicative parameter which reflects the tendency of things wrapped around a spindle to tighten further. The effect is a function of the coefficient of friction and the wrap angle (in radians) and is given by

$$\frac{T_o}{T_i} = e^{\mu\phi} \qquad (6.2.10)$$

Where:
T_o = output tension
T_i = input tension
e = 2.71828
μ = coefficient of friction
ϕ = angle of wrap, rad

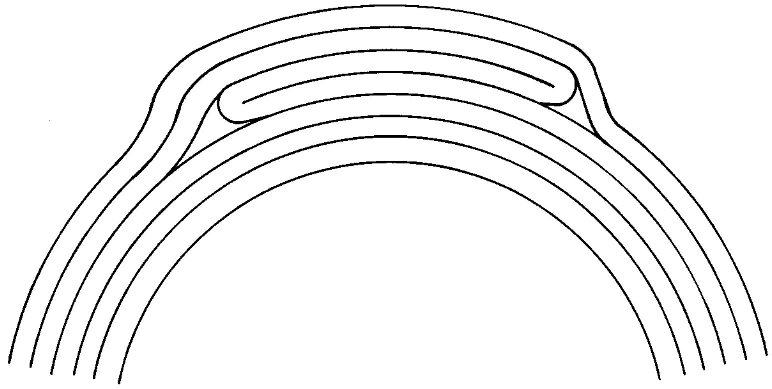

Figure 6.2.14 Cinching, or interlayer folding of tape in winding.

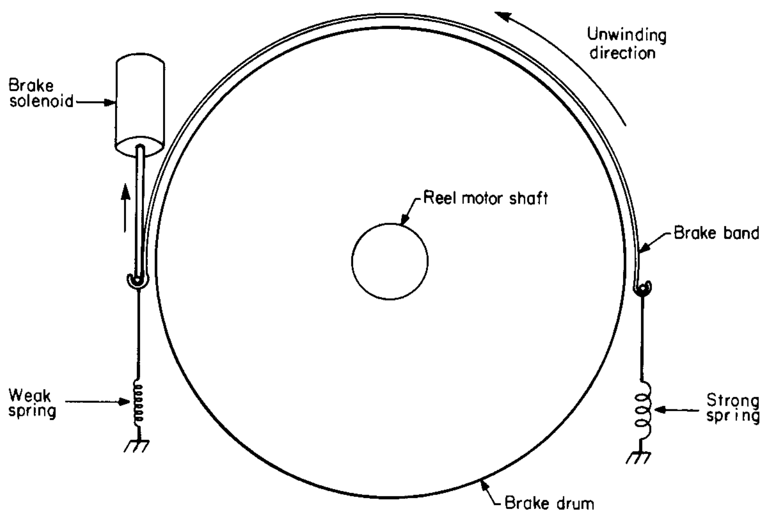

Figure 6.2.15 Tension brake operation.

The effect is a function of the angle of wrap. It is overwhelming in nautical applications, in which a few turns of rope can multiply the holdback force of a sailor by millions. The angle of wrap of tape around the nosepiece of a head is so small as to seem negligible but, when multiplied by (not summed with) the effect of each wrap around each frictional element that the tape encounters, can result in a ratio of output tension to input tension approaching 2:1. The coefficient of friction of typical tape against typical polished metal surfaces ranges between 0.2 and 0.3 when the tape is in motion and about twice that when it is stationary.

Depending on tension and the surface roughness of the tape, there is a tape speed (approximately 5 in/s) above which friction is reduced somewhat. It results when the air film between tape and guide exceeds the roughness of the rubbing surfaces.

Supply and takeup tension arms, in simple systems, serve only to supply some tape to the head assembly upon start-up while the supply reel accelerates. This diminishes the tension transients associated with starting and stopping tape motion. In more complex systems, the position of the tension arms is sensed and used to regulate the torque applied to the associated reels.

Variations in holdback torque due to motor cogging or to an off-center tape pack on the reel will tend to vary the tension (and therefore the elongation) of the tape and thus result in variations in tape velocity at the playback head. The supply idler suppresses this tendency by coupling the tape to a rotating member having high inertia, thus tending to isolate the tape motion at the head from disturbances at the supply reel.

The inertia of the idler is a compromise. Too much, and the time from the beginning of play to stable speed is excessive, as the tape slips over the idler until the idler is fully accelerated. If there is too little inertia, the isolation is insufficient.

In some film transports, the idler is given a jump start (by independent means) at the beginning of the play cycle instead of depending on the film to accelerate the idler. This minimizes the time between the start of the play mode and stable motion.

The difference between stationary friction and moving friction gives rise to the *stick-slip* (or *violin-string*) phenomenon, also called *scrape flutter*. The effect is most pronounced when the span of tape between stationary frictional elements is relatively large, as in professional transports. In the case of tapes improperly stored so that the plasticizers and lubricants have evaporated, the effect can be so pronounced as to render the tapes unusable.

The flutter idler helps to diminish the high-frequency flutter component associated with scrape flutter by lightly coupling the tape to an inertial element. The roundness of the idler and the quality of its bearings (usually jeweled) are important, as any deviations from uniformity will directly perturb the tape motion. The angle of contact is usually small, on the order of 1 or 2 degrees.

Contact of the tape and the erase, record, and playback heads is assured by having the tape subtend a total angle over the nose of the head on the order of 10 to 16 degrees. This is shown in Figure 6.2.16. In consumer-grade cassette recorders, contact is assured by a felt pad which presses the tape against the head.

The tape-path element which determines the absolute speed of the tape is the capstan. In some designs, the capstan is coated with a plastic having a high coefficient of friction, and the wrap angle is high, 90 to 270 degrees. Reel servos are used to maintain relatively constant tape tension so as to restrict the work done by the capstan. This limits the possibility of slippage of the tape over the capstan.

In typical designs, a manual or solenoid-operated rubber roller presses the tape against a steel shaft. Figure 6.2.17 shows two circumstances. In the first, the roller is narrower than the tape. In this case, the tape speed must be calculated by using the radius of the capstan shaft plus one-third of the thickness of the tape. In the second case, it must be assumed that the coefficient of friction of rubber and tape is greater than that of steel and tape; thus the capstan drives the roller, and the roller drives the back side of the tape, while the front side of the tape slips over the shaft. The rolling radius of the roller depends upon its elasticity and the pressure against the shaft. It is a complex relationship usually best resolved by measurement.

Measurement of absolute tape speed can be approximated by reproducing a flutter-measurement tape and measuring the reproduced frequency, typically 3000 Hz, nominal. The percentage

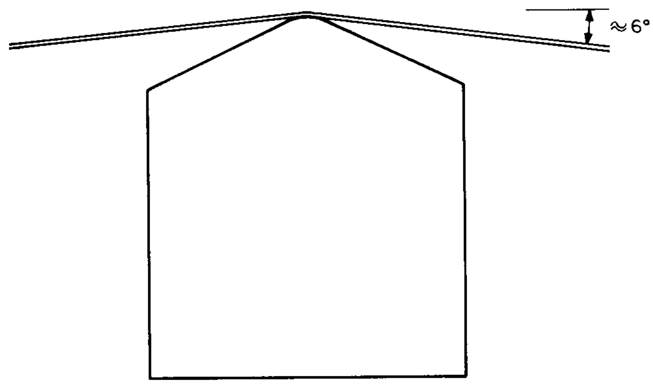

Figure 6.2.16 Head-to-tape contact by wrap.

by which the frequency deviates from 3000 Hz is the percentage by which the tape deviates from the design value.

The takeup arm serves much the same purpose as the supply arm, isolating the capstan from transients produced at the takeup reel.

6.2.4b Capstan and Reel Servos

Figure 6.2.18 shows, in schematic form, the operation of a reel servo. The tension arm is fitted with a spring, which determines the tape tension. The position of the arm is sensed by a potentiometer (or other means). Any deviation from the desired deflection of the arm causes the motor torque to be adjusted so as to reduce the deviation toward zero. In some designs, any tendency to oscillate is damped by a *dashpot*, a piston in a cylinder with a leak. The leak is often adjustable. Usually, servomechanisms are applied to both supply and takeup reels.

The frequency response of the reel-servo system must take into account the resonant systems formed by the inertia of the reel and motor, the spring constant of the tension arm, the mass of the arm, the modulus of elasticity of the tape, the length of tape between the reel and the supply idler (or capstan), and the moment of inertia of the idler (or capstan). Considerable insight into the performance of a proposed design can be gained by modeling the mechanical components as electrical elements and using one of the many computer programs designed to analyze the response of electrical circuits.

A capstan servo is a *rate servo*, in which the rotational rate of the capstan is compared with a reference frequency and any deviation from the reference rate causes an increase or decrease in capstan speed, so as to tend to reduce differences in rate to zero. The capstan shaft is fitted with a tachometer disk, usually optical, which generates a frequency, typically 9600 Hz, at normal play speed. The capstan tachometer frequency is compared with a reference derived from a crystal or the scanning frequency of a television system. The result of the comparison varies the current to the capstan motor so as to maintain phase coherency of the tachometer and the reference. While

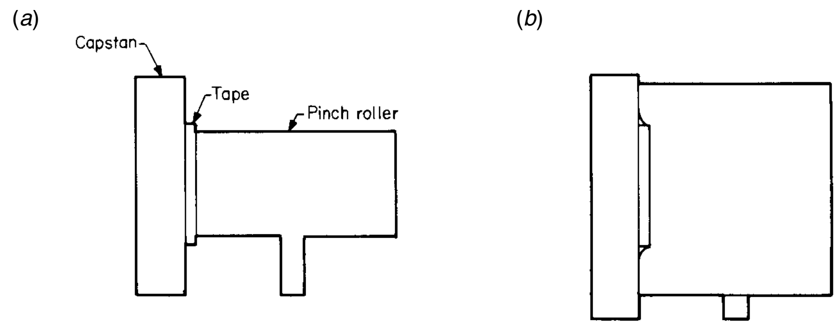

Figure 6.2.17 Capstan pinch-roller relationships: (*a*) capstan moves tape, tape moves roller; (*b*) capstan moves roller, roller moves tape.

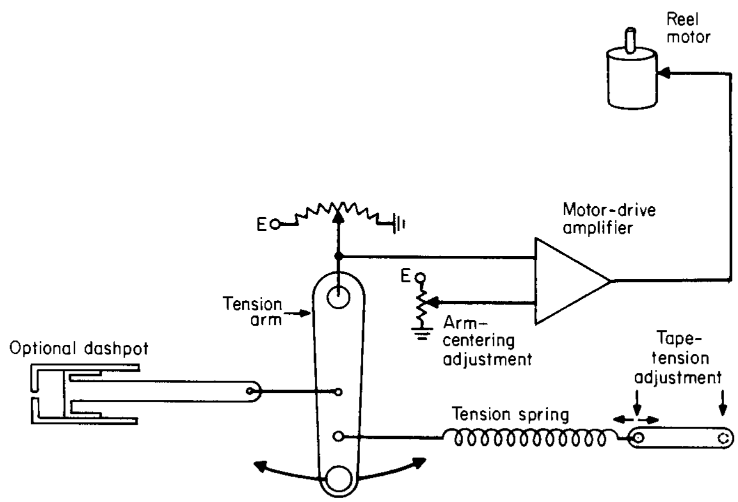

Figure 6.2.18 Simplified reel-servo arrangement.

this guarantees a constant rotational rate of the capstan, it does not cause a precisely repeatable tape speed, since the dimensions of the tape can change with time.

To maintain time coherency with another device, typically a film or television camera, it is necessary to record, on the audio transport, a signal derived from the motion of the film camera or the scanning rate of a television camera. During replay, the film or TV rate is compared with the replay of the record, and any tendency to depart from phase coherency is caused to vary the capstan speed so as to diminish that tendency toward zero. In this way, audio recorded separately from video can be reproduced in lip synchronism.

6.2.4c Sources of Flutter and Wow

There are a number of potential sources of flutter and wow in an analog audio tape recorder. Some of the more common include the following:

- Variations in the supply-reel/takeup-reel torque, caused by motor cogging, poor ball bearings, out-of-round mounting of the turntable, dragging brakes, out-of-round tape pack, or the scraping of bent reel flanges against the edges of the tape. The effect of these variations is reduced by the inertia of the supply/takeup idler and by the effect of the reel servo, if present.
- Out-of-round tension arm idlers or bad ball bearings. These effects tend to be diminished by the inertia of the supply/takeup idler and possibly by the reel servo, depending on frequency.
- Out-of-round supply/takeup idler or bad bearings thereon. These will not be much diminished by the reel servo.
- Scrape flutter in the absence of a scrape-flutter idler or out-of-round condition in the presence of one. This is not diminished by servos.
- Out-of-round capstan. This is undiminished by servos.
- Off-center mounting of a tachometer disk to the capstan shaft. This condition will cause the servo to generate perturbations at the once-around rate.
- Bad bearings in the capstan or pinch roller. These will be diminished by a capstan servo depending on ball size (frequency) and the response of the servo.
- Vibration of portable recorders, especially angular vibration in the plane of the reels. This effect is diminished by servos, but since all rotating elements are involved, it is very easy to overload some servo systems by exposing them to excessive vibration. Some cassette designs are equipped with counterrotating inertial elements which are designed to cancel the angular acceleration induced by a running person.
- Slippage of the tape over the capstan due to insufficient pressure of the pinch roller or, in a pinch-roller-less design, due to the debris which has attached itself to the somewhat tacky plastic capstan surface, thus giving it a reduced coefficient of friction.

6.2.5 References

1. Heaslett, A. M.: "Phase Distortion in Audio Magnetic Recording," presented at the 55th Convention of the Audio Engineering Society, preprint 1178, P-3, October 1976.
2. "Time and Control Code for Video and Audio Tape Recordings for 525-Line/60 Field Television Systems," ANSI V98.12M, American National Standards Institute, New York, N.Y., 1981.
3. "Time-and-Control Codes for Television Tape Recordings (625 Line Systems)," EBU TECH 3097-E, Technical Centre of the EBU, Brussels, April 1972.

Chapter

6.3

Analog Recording Formats

E. Stanley Busby

6.3.1 Introduction

A wide variety of analog audio recording formats have been developed over the years to satisfy specific needs and applications. This chapter provides the basic specifications of the most common systems. Although many of the formats documented here are no longer used in a modern audio facility, these formats are important for the audio professional if for no other reason than preserving archived materials.

In the sections that follow, track-width dimensions shown are for the recorded tracks. Where erase heads are separate, it is usual practice for the head width of the erase gap to be 0.010 to 0.020 in wider than the track width to assure full erasure on an interchange basis. Similarly, where reproduce heads are separate, it is typical for their gaps to be 0.005 to 0.010 in smaller than the track width to assure constant output with variations of tracking accuracy.

6.3.2 Two-Track Cassette System

In terms of the number of manufactured recorders, the 0.150-in-width two-reel cassette is undoubtedly the most popular analog audio format ever designed. These cassettes can be found in automobile dashboards and are worn by joggers in the park.

In the simplest form, there are two monophonic tracks, one to each side of the centerline of the tape. When one side is completed, the user removes the cassette, flips it over, and plays the second side over the same head used for the first side. The same method is used on simple stereophonic recorders. Figure 6.3.1*a* illustrates the monophonic case, and Figure 6.3.1*b* the stereo case.

Many recorders, especially automotive installations, offer an autoreverse feature. When the first side of the tape has been completed, the physical end of the tape is sensed, the capstan is reversed, and play in the opposite direction begins.

In some machines, the single head or single stereo pair of heads is moved downward until it is in the position shown at the bottom of the tape in Figure 6.3.1*a* and *b*. In other implementations, separate heads or head pairs are provided for the reverse direction, with electronic switching choosing the proper head or heads.

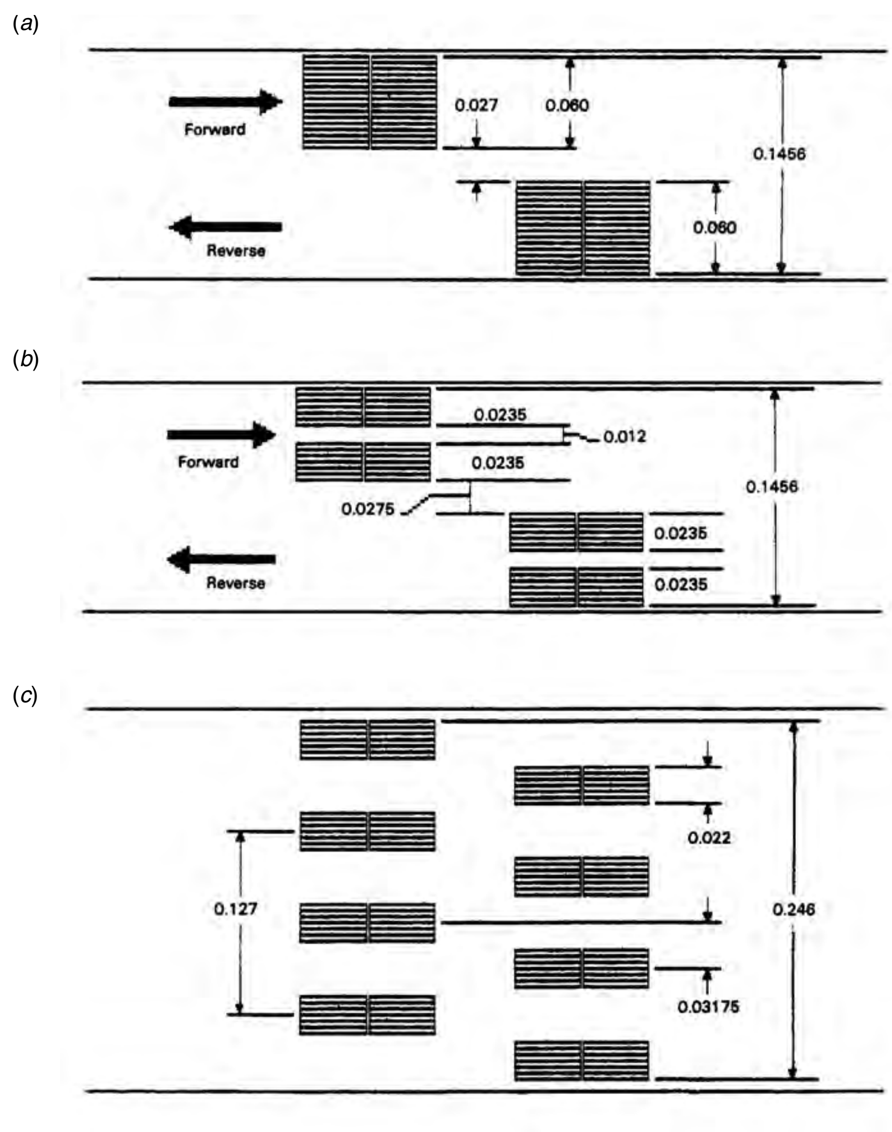

Figure 6.3.1 Cassette formats: (*a*) monophonic recording tracks, (*b*) stereophonic recording tracks, (*c*) eight-track recording tracks.

In monophonic applications requiring long playing time, such as talking books, it is typical to use the stereo format to squeeze four separate tracks onto one tape. The reproducer must have a left-right balance control capable of reducing the output of each channel to zero.

The eight-track cassette format is shown in Figure 6.3.1*c*.

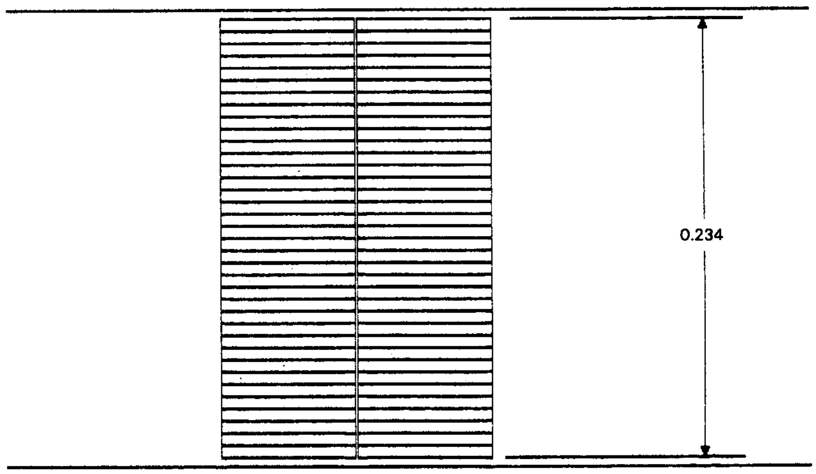

Figure 6.3.2 1/4-in full-track recording format.

6.3.3 Reel-to-Reel Formats

The number of these formats is quite large, for it includes a wide range of tape widths, with each tape width supporting a number of tracks.

The simplest of the 1/4-in formats is called *full track*. A monaural format, it is shown in Figure 6.3.2. Capable of superlative performance, it is used mostly in monaural amplitude-modulation (AM) and shortwave broadcasting. An early stereo format which also supports two independent channels (as in the case of two languages) is shown in Figure 6.3.3. The spacing between the two tracks provides adequate isolation. This format also allows for a monaural implementation in which the tape is flipped over to play the second side, similarly to the way in which cassettes are played. In this case, the lower of the two heads shown in Figure 6.3.3 may be omitted. When this format is used for recording stereo associated with a film or videotape recording, it is customary to record a neo-pilot-tone or time code on two very narrow (about 0.016-in) tracks which are very close together and located so as to straddle the centerline of the tape width. The two heads are located in a separate head stack and are driven in antiphase to reduce crosstalk to negligible proportions.

A European stereo-only format is depicted in Figure 6.3.4. This format makes a tradeoff between increased channel crosstalk, which is allowable in a stereo system, and a better S/N resulting from the wider track width.

A bidirectional stereo format is shown in Figure 6.3.5. As in the case of the cassette format, a particular implementation may furnish only the heads identified by the right-pointing arrows, requiring the user to flip the tape reel midway, or it may furnish all four heads for use on machines equipped with autoreverse mechanisms. Prerecorded music using this format has a sliding low-frequency tone ranging from 15 to 20 Hz recorded at the end of the first side.

The 1/2-in stereo master format, used in recording studios and for other professional applications, is shown in Figure 6.3.6. The wide tracks provide very low noise. This format, usually

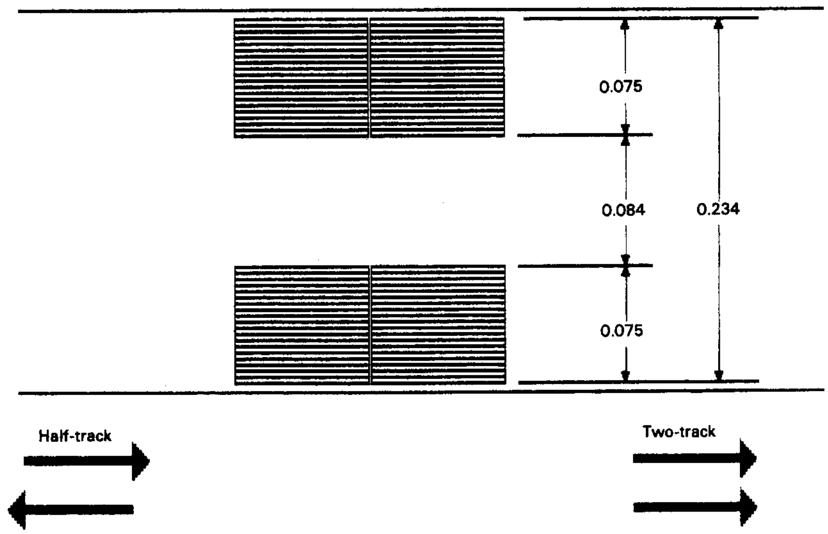

Figure 6.3.3 1/4-in two-track-half-track format.

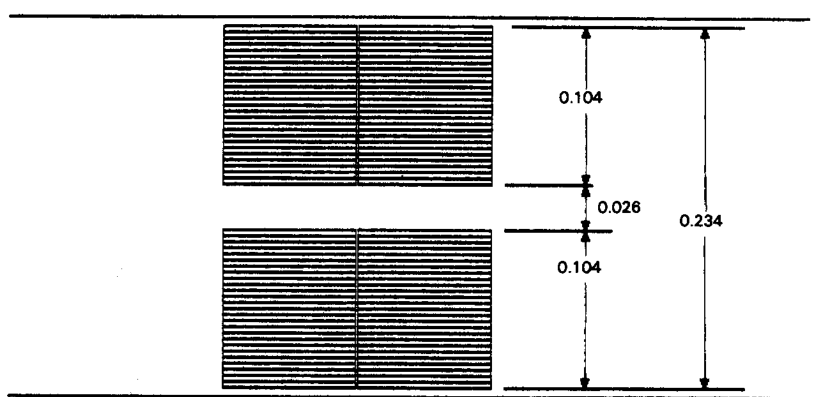

Figure 6.3.4 1/4-in stereo-only format.

operated at 15 or 30 in/s, is often used to convey the final two-channel mix-down of an audio production.

A few quadraphonic tapes were published toward the end of the popularity of this format. The appropriate format drawing is Figure 6.3.7. Figure 6.3.8 shows another four-channel implementation, but using 1/2-in tape. Aside from general multitrack recording, this format is often used as the master tape to be copied onto the cassette stereo format. In this case two stereo pairs are copied at once, one in reverse. Both the 1/2-in reproducer and the cassette recorder are operated

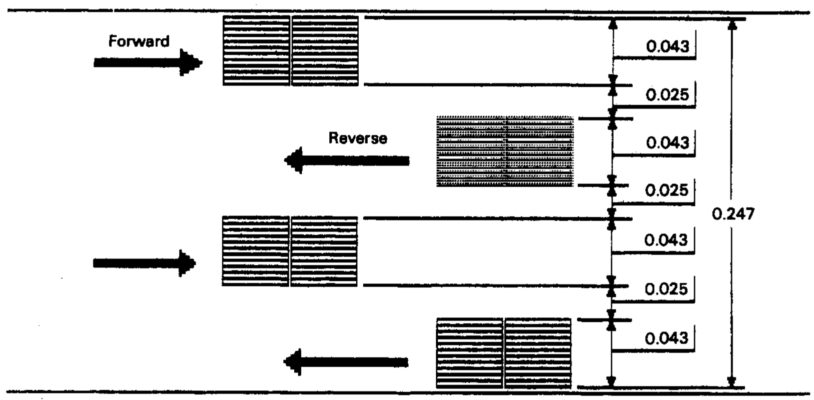

Figure 6.3.5 1/4-in bidirectional stereo format.

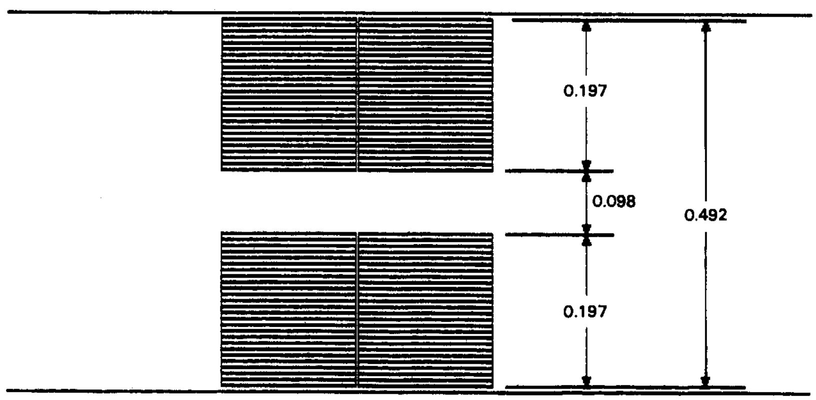

Figure 6.3.6 1/2-in stereo-master format.

at a high speed, usually an integer multiple of normal play speed. By these two means, copying time is minimized.

The 1/2-in four-track format was simply repeated, as shown in Figure 6.3.9, to provide an eight-track 1-in format. The first use of a multitrack recorder to allow a single performer to perform several different parts was on an eight-track 1-in recorder used by the performers Les Paul and Mary Ford. Using the record head as a reproduce head, the performer, listening with headphones, was able to maintain tempo while recording another part onto another track.

The number of tracks was increased by the use of 2-in-wide tape, already a popular tape width for early video recorders. The two format drawings are Figures 6.3.10*a* and *b*. While the typical

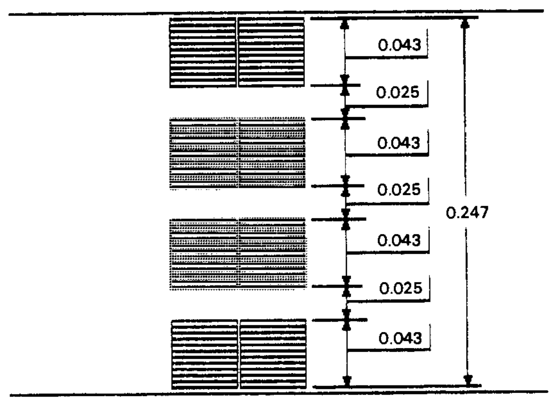

Figure 6.3.7 Quadraphonic format.

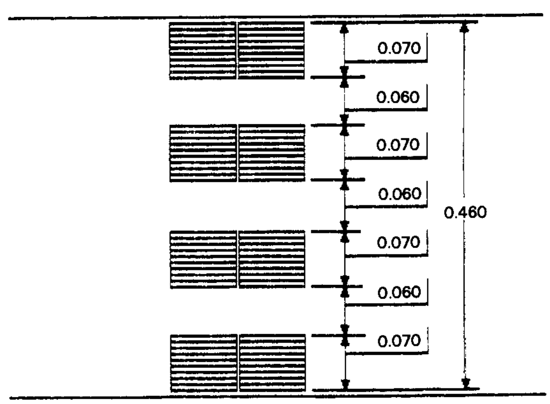

Figure 6.3.8 1/2-in four-channel or four-track stereo-master format.

tape speeds of multitrack recorders are 7.5, 15, and 30 in/s, all offer variable-speed reproducing, and some allow small deviations in record speed.

6.3.3a Audio Recording on Video Recorders

Video recording formats typically provide for two to four associated audio tracks. Analog recording, for the most part, uses the same methods as with audio recorders, with the tracks located at or near the edges of the tape. One audio track is usually dedicated to the recording of the time code. Similar technology is used to record the control track, which is essentially a record of the phase position of the rotating video head assembly. Recorded on another longitudinal

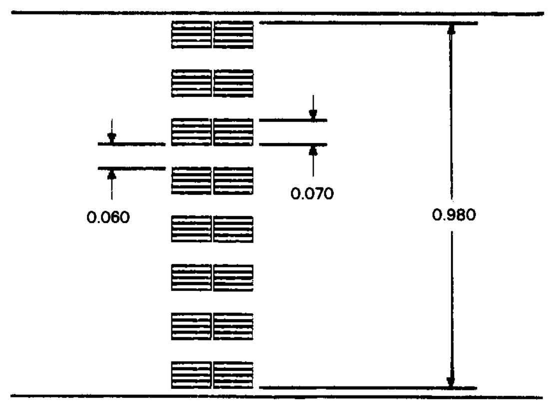

Figure 6.3.9 1-in eight-track format.

track, the playback control-track signal is compared with the phase position of the video head, and any difference is used to control the capstan so as to reduce the difference.

Video recorders use very short wavelengths for the video channel, so there is nothing to be gained by using thick tape coatings. Video tapes therefore have thin coatings. This causes the 3-dB frequency of the reproduce equalization curve to be higher than in an equivalent audio-only application. It also reduces the output available at the reproduce head, which, coupled with the many sources of magnetic pollution on a video recorder, makes the control of induced noise difficult.

Digital video recorders use even shorter wavelengths than analog recorders. Tape coatings are about half the thickness of analog video tapes (about 100 μin).

6.3.3b Overview of Format Developments

Many more tape formats exist or have existed than are described here. Early stereo research and demonstrations used a three-track format on 1-in tape or coated 35-mm film. There are a few machines offering eight tracks on 1/4-in tape and 12 or 16 channels on 1 -in tape. One long-duration recorder used a rotary disk having four heads around its periphery. It recorded narrow tracks transversely across 3-in-wide tape. The method is quite similar to that used on the first 2-in video recorders. The recording time was on the order of 24 h. Before the advent of the cassette recorder, a magnetic-disk recording system called a *mat recorder* was devised to differentiate it legally from a reel-to-reel recorder. Music was recorded in a fashion similar to the vinyl disk, in a spiral track, on a round, about 0.005-in-thick, flat magnetically coated substrate. Developed in response to certain union rules, this system suffered a quick demise.

In addition, a large number of recording formats have evolved for magnetically coated film. Film widths range from 8 to 70 mm and include 16-, 17.5-, and 35-mm film widths. Track usage is twofold: magnetically striped film, which also contains an optical image; and magnetically coated film totally devoted to audio recording.

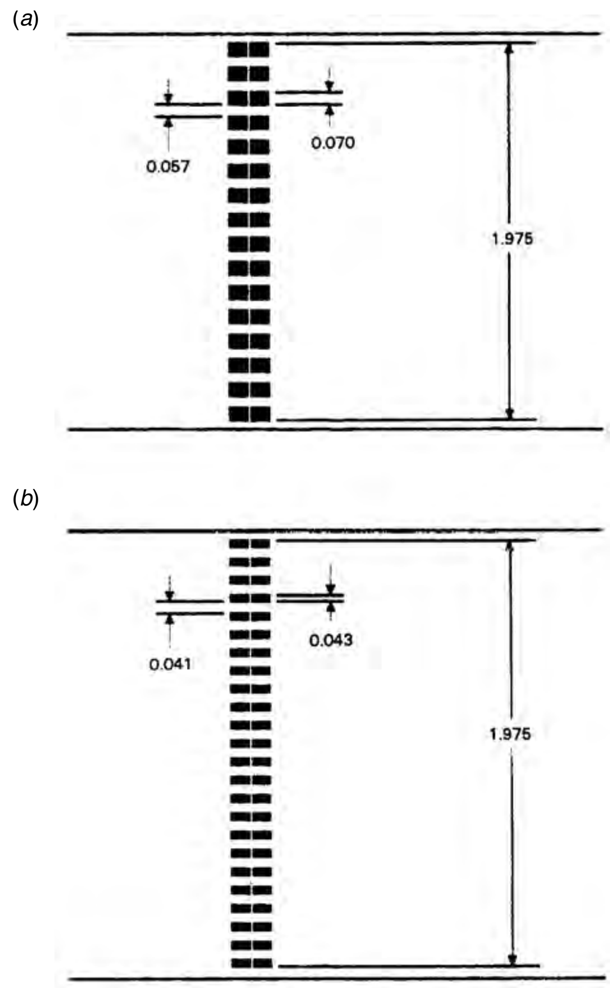

Figure 6.3.10 Typical 2-in multitrack formats: (*a*) eight-track, (*b*) 24-track.

Many of the formats are maintained only by manufacturers who supply replacements for worn-out heads. These manufacturers are the best source of data relating to supported formats.