Analog Recorders

Sound recording has taken many forms as technological developments created new and improved ways of storing information. The earliest attempts to capture and reproduce sound used mechanical methods, as Edison's machines that connected a large horn to a tiny stylus that traced grooves in a rotating cylinder. Optical systems have long been used for film sound, but analog optical systems are complicated to record and tend to be noisy. The system best adapted to sound recording has been the magnetic approach, where the sound is converted first to an electrical analog and then to a proportional magnetic flux that leaves a pattern of magnetization on a medium that can retain the signal for a long time.

The earliest magnetic recorders used steel wire or ribbon, an obvious approach based on the understanding of iron's ability to be magnetized. But steel wire was inconvenient, not to mention dangerous, so the practical magnetic recorder would have to wait for the development of better magnetic materials. The breakthrough that opened the way to modern recorders was the use of magnetic oxides glued to flexible tape. This allowed the creation of reliable recorders with easily interchangeable media and started the tape recorder revolution. The hard drives we use today are directly descended from magnetic tape and, although the encoding is different, operate under the same physical constraints as analog tape recorders.

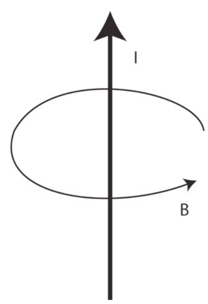


Fig. 1: Current I produces magnetic field B

An electric current always produces a proportional magnetic field, a basic property of electromagnetism. Current flowing in a straight wire generates a magnetic field that curves around the length of the wire and spreads out in space, diminishing in amplitude with the square of the distance from the wire. The magnetic field orients in what's known as the "right-hand rule": if the current flow direction is indicated by the right thumb, the magnetic field is in the direction of the fingers. If the wire is instead wrapped around a piece of iron, a magnetic field will be generated within the iron, creating an electromagnet. Iron has a low resistance to the magnetic flux (the magnetic equivalent of electric current), called reluctance (the magnetic equivalent of resistance.). The type of magnetization produced in iron is known as ferromagnetism. This type of magnetization can persist after the applied current or external magnetic field is withdrawn, making it ideal for storing magnetic patterns. Other types of magnetization (paramagnetism and diamagnetism) occur, but do not persist after the applied force is removed and are therefore not of interest in the pursuit of making recordings.

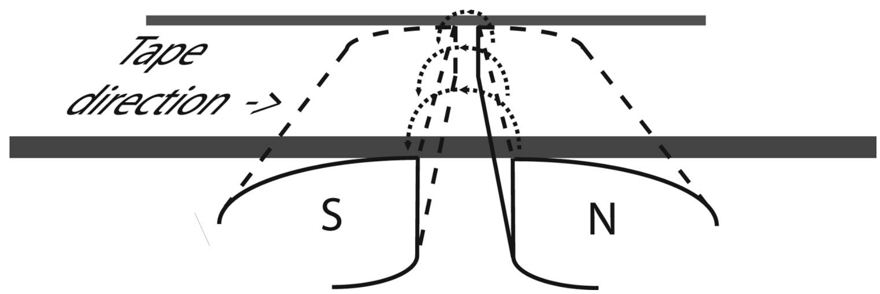


Fig. 2: Part of the magnetic field at record head gap (size exaggerated)

If the metal form is shaped into a ring with a small gap, the magnetic flux will flow in the iron until it reaches the gap, at which point it will flow into space in all directions. If we then introduce a magnetic medium in close proximity to the gap, the magnetic lines of force will tend to flow through the magnetic material because it has less reluctance than the air. As the magnetic material is moved past the head gap, there will be a pattern of magnetization retained on the medium as the magnetic domains, functionally tiny bar magnets, align their fields with the applied field. Once the applied magnetic field strength is reduced to a level insufficient to further change the magnetization of the medium, the magnetization pattern left on the medium will be retained. The actual recording occurs at a distance from the record head gap because the applied field spreads out in space and the point at which the field strength drops below the threshold necessary to further alter the polarization of the domains occurs away from the actual gap. The system requires the medium to be moved past the writing head at a known and constant rate. The geometry of the head, its gap, and the magnetic medium will determine how accurately the signal is written. It is important to understand how magnetic fields behave as this is fundamental to how a signal can be transferred to magnetic media.

Magnetic media are made of tiny particles of magnetic materials glued to a substrate. The particles do not move physically, but rather adjust their magnetic polarities to align with an applied field. The basic structural element of magnetization is the domain, conceptually a tiny magnet with a north and a south pole, referred to as a dipole. Domains are areas of a magnetic material in which the unpaired outer electrons' spins interact to produce aligned magnetic dipoles. Domains do not correspond exactly with particle size or shape and many domains may be contained within a single particle. Each of these domains can be aligned in one of two opposite directions (N-S or S-N) by an applied magnetic field. If there are many of these domains attached to the medium in random orientations, patterns of retained magnetization can be created by moving the medium past the applied field while it is changing in proportion to the electrical signal. The minimum field strength required to alter the polarization of a medium is called the coercivity of the medium, a measure of how hard it would be to record or erase the magnetic signal. Some magnetic materials are easy to magnetize and lose their magnetization easily. These are called soft magnetic materials and are used in transformers and sensors. Other materials are more difficult to magnetize, retain their magnetization better and are known as hard magnetic materials. These are employed in motors, generators, and actuators like solenoids. In between are the materials used for magnetic recording, where intermediate coercivities allow recording and erasure at field strengths available from magnetic heads.

Although we are most familiar with magnets made of iron and alloys with other metals, the atoms of certain other elements are capable of ferromagnetization: nickel, cobalt, chromium, manganese, gadolinium and dysprosium. Atoms of these elements exhibit the quantum electron spin effect known as exchange coupling that allows the magnetic dipole moments of adjacent atoms to align into a magnetic field. Since the atoms of these elements produce the magnetic field, salts of these elements are also capable of magnetization. These salts, mostly oxides, are used as magnetic materials in magnetic tape and discs. Newer tape formulations used for video and digital audio use metal particles and evaporated metal coatings to achieve higher coercivities.

The fact that there exists a minimum magnetic field strength required to begin altering the polarity of the domains leads to one of the limitations of magnetic recording. Because there is no effect when the signal strength falls below the threshold for magnetizing the material, low-level signals are not recorded. At very high field strengths, all of the domains are polarized and no further signal amplitude can be recorded. This leads to a compression effect that can be exploited in analog recording, but it is a non-linear distortion of the signal. Once the maximum level has been recorded on the medium, reversing the field does not immediately cause a reversal of the magnetization of the medium until the applied field exceeds the threshold amplitude required to change the magnetic polarization previously written to the medium. This phenomenon is known as hysteresis and causes yet another non-linear form of distortion.

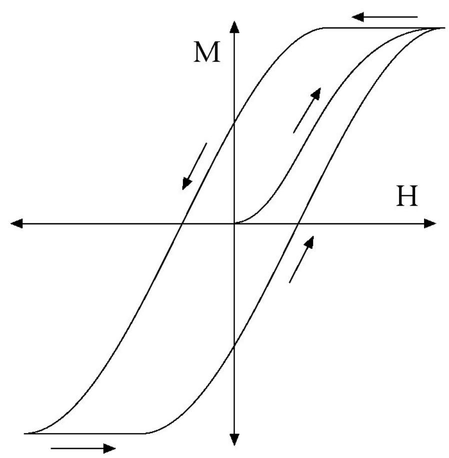


Fig. 3: Magnetic hysteresis

In Figure 3, H is the applied magnetic field (in oersteds, Oe= $1/4\pi \times 10^3$ A/m) and M (Oe) is the retained, or remanent field. As the applied field strength grows in the positive direction, it begins to change the magnetic particles' magnetic field alignments, increasing until no domains remain to be magnetized. As the applied field strength decreases, the magnetization remains until the reversing applied field exceeds the threshold for reversing the retained magnetization. While some of the curves have linear regions, the extreme low and high-level signals will be distorted in such a system. In the case of digital recording, where we need only to record two discrete levels or polarization directions, the non-linearity is not so important but for analog recording it is a serious problem.

Early magnetic recorders used DC bias to offset the signal along the initial rising curve and utilized only the small linear segment. Since the magnetization always produced a field with the same direction, it resulted in eventual magnetization of the heads themselves. It also resulted in noisy recordings since so little of the M-H curve could be used. The discovery of AC bias, where a large amplitude high-frequency sinusoidal signal is mixed linearly with the audio signal, made the entire range of the curves accessible and allowed the development of modern high-fidelity magnetic recording. The bias signal frequency is five to ten times higher than the highest audio frequency and it is poorly recorded itself, yet it improves the linearity of the audio signal reproduced. Many explanations have been offered about how AC bias acts to linearize the hysteresis curve because the discovery was reportedly an accident, albeit one that opened the door to the modern era of sound recording. To understand what AC bias does to eliminate the non-linearities of the hysteresis curve we will examine the different ways of explaining the effect.

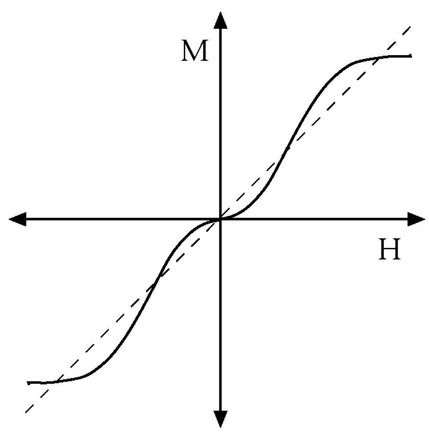


Fig. 4: Applied (H) versus retained (M) magnetic field

If we try to record a sine wave signal directly with no bias, we find the region of the signal around the 0 field strength level is not able to cause any magnetic particles to reorient their polarization and therefore no signal is recorded. As the signal increases, the magnetic field applied by the head starts to exceed the threshold for magnetizing the medium and a signal is recorded. As the amplitude increases further, more domains are affected and more magnetization is left on the medium. As the signal increases further, it eventually magnetizes all of the susceptible domains and no further signal can be recorded. The result is a sine wave with a distorted area around zero crossing and a flattened top.

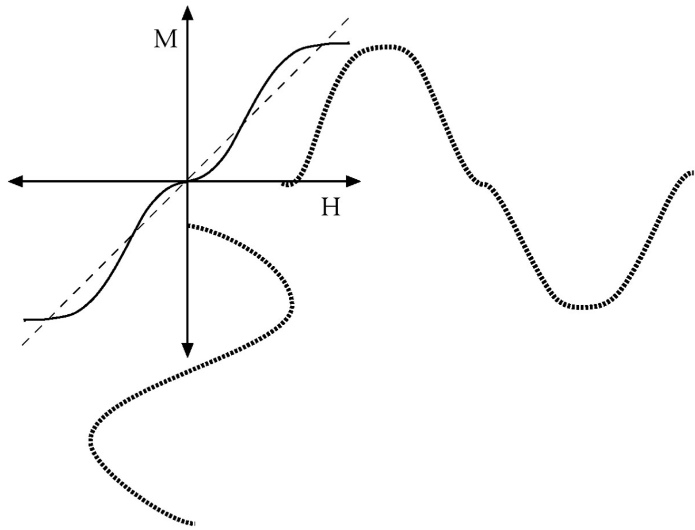


Fig. 5: Sine wave input is distorted

If we add a large-amplitude, high frequency sinusoidal signal to the audio signal, the composite signal can be fed to the record head and used to magnetize the medium. Since the two signals are simply added together, they can easily be separated by filtering. The resulting audio signal is played back with greatly reduced distortion. While the bias signal is itself distorted at the zero crossing, the envelope of the bias signal plus the audio signal is not affected. Since the bias signal is poorly reproduced due to its high frequency and does not contaminate the signal recovered by the playback head gap, the remaining audio signal is recovered without zero crossing distortion.

AC bias has been described as a reduction of the inertia involved in aligning the domains with the applied field, sort of “shaking up” the magnetic domains so that it is easier to affect their magnetic polarization. Since the domains do not physically move, this explanation is a bit confusing, although it does address the issue of low field strengths failing to alter the magnetization of the medium. What bias current does is increase the average level of applied field, enabling the magnetization of low-level signals that would otherwise be too small to change the polarizations of any domains. The effect of AC bias is referred to as anhysteretic magnetization. In the reproduction process, the high frequency bias signal is filtered out by the reproduce head without altering the lower frequencies, resulting in a linearized response to the low level signal. Care must also be taken to prevent the bias signal from contaminating other parts of the record circuitry, thus bias trap filters are used to keep the bias signal out of the record electronics.

The adjustment of the amount of bias added to the record signal gives the recordist the ability to select a balance between noise performance, distortion, and bandwidth. (See Figure 6 below.) The interaction of bias level with these parameters allows a trade-off between these factors that gives the engineer the ability to optimize for the desired characteristic. By increasing the amount of bias, a peak in the amplitude of the retained signal can be determined. Further increasing the amount will decrease the amount of high frequencies stored while decreasing distortion and noise. The exact amount of bias used varies with the type of tape used. Tape manufacturers will recommend a specific amount of "over-bias" be used to provide the claimed performance of the tape, but such a determination is open to the interpretation of the user, who may choose a different balance of noise and distortion from that recommended.

The magnetic field applied by the record head interacts with the tape in a complex way. Since the tape has a finite thickness, magnetic particles at different depths in the tape experience different applied field strengths. This effect is wavelength dependent and therefore varies with frequency. Since the signal is actually recorded where the applied field decreases to the threshold for particle magnetization, it occurs at a distance from the head gap itself, the so-called "trailing edge". This distance is also wavelength dependent. The transfer of magnetization from the head to the tape is critically dependent on the distance from the gap, thus any separation of the tape from the head results in a diminished retained signal, a phenomenon we call a "drop-out". This is similar to the reduction of retained magnetization with increasing depth into the magnetic medium. The geometry of the tape and head determine much of the efficiency of the recording process. The same is true for the reproduction process, although the details are different.

The equation relating the reproduced voltage (V) and the flux seen by the head is:

$$V = -\Delta\Phi / \Delta t = -Nv(\Delta\Phi / \Delta x),$$

where:

Φ = average gap flux
t = time
v= velocity
x = position
N = number of turns of wire in the head.

This shows that the output voltage is a function of the rate of change of flux on the tape, with the reproduce head converting the change in the average flux in the gap to a voltage. This is similar to an inductor where the voltage is proportional to the rate of change of the current. Since the rate of flux change increases with increasing frequency (decreasing wavelength) of the recorded signal, the output voltage increases with increasing frequency. (It will also increase if the tape is pulled past the head faster.) This results in a 6 dB / octave rise in output voltage. The low and high frequency roll-offs created by the physics of the reproduce process require that the reproduced signal be equalized electronically in order to restore the original signal. Many different "standard" equalization curves exist and tape and recorder manufacturers generally specify which they deem best suited to their products.

The reproduce gap generates an output voltage that depends on the change in average flux sensed by the head gap. This means that when the wavelength of the signal is exactly the length of the gap, the average flux is one complete sinusoid generating an average flux of zero. Therefore, a signal at that frequency will produce no output: the gap length of the play head determines the maximum frequency signal that can be reproduced. In the case of the record head, the applied field strength causes the signal to be recorded and the larger the record gap, the more field that can be generated and the more signal that can be recorded. There is a basic difference between the record and play functions so the gap length plays a different role in the two cases. The record gap should be large enough to create a magnetic field deep into the tape magnetic coating. The reproduce gap should be large to capture the most flux change but small to allow short wavelengths to be reproduced. Obviously there is a trade-off inherent in the playback head gap dimensions.

The equation approximating the output voltage [e(x)] from a magnetic recorder reproduce head is:

$$e(x) = -\mu_0 V w M_0 (H_g g/i)\, k\delta\, [e^{-kd}]\, [(1-e^{-k\delta})/k\delta]\, [\sin(kg/2)/(kg/2)]\, \cos(kx),$$

where:

- x = longitudinal position (Vt [velocity x time])
- $e(x)$ = voltage output from longitudinal magnetic recording
- μ_0 = magnetic permeability of a vacuum
- V = tape to head velocity
- w = track width
- M_0 = peak value of sine-wave magnetization
- H_g = deep gap field
- g = gap length
- i = current in head coil
- k = wave number ($= 2\pi / \lambda$) where λ = wavelength
- δ = thickness of the magnetic medium
- d = distance from tape to head

As is clear from the equation, many physical characteristics of the playback head and tape affect the recovered electrical signal. The terms in square brackets are loss terms relating to specific physical relationships that act to reduce the output voltage at the reproduce head:

<u>Spacing Loss</u> (decrease in output signal due to distance from tape to head):

$$L_d\ (\mathrm{dB}) = 20 \log (e^{-kd})$$

Spacing loss increases exponentially with increasing distance as a ratio of the wavelength of the signal, thus high frequencies are more susceptible to drop-outs. (Spacing loss can be expressed as 54.6 dB / wavelength distance, meaning that almost 60 dB of drop-out is produced if the tape is separated from the head by the wavelength of the signal of interest!) Preventing high frequency drop-outs from dirt particles requires that heads and transports be kept clean as even microscopic particles cause significant drop-outs.

<u>Gap Loss</u> (decrease in output signal due to the length of the gap)

$$L_g\ (\mathrm{dB}) = 20 \log (\sin(kg/2)/(kg/2))$$

Gap loss reflects the fact that the reproduce head responds to the average flux in the gap: therefore when the wavelength of the signal just equals the gap length, the average flux from one sine cycle is zero and there is no signal produced. The effective gap length is 14% larger than the actual gap length due to fringing of the magnetic field and other factors. While gap loss is often assumed to be the dominant limitation to high-frequency reproduction, reproduce gaps of lengths commonly used in professional recorders do not produce significant loss even at frequencies well above 20 kHz. For example, the Ampex ATR-100 series recorder employs a playback gap length of 2.5 μ, producing a first null at over 150 kHz at 38 cm/s (15 in/s) and a –3 dB point of 61 kHz. Reproduce gaps range from 1.5 to 6 μ.

Where gap losses may become important is in the case of synchronous overdubbing, when the record head is used to play back tracks already recorded to other tracks. Since record head gaps are longer to generate large record fields, the lengths may severely degrade the playback response due to gap losses. Record gaps range from 4 to 13 μ in modern machines. For a record gap of about 13 μ, the ATR-100 series recorder will have a first null at about 30 kHz, well below that of the reproduce heads.

At low frequencies, the gap senses magnetic fields that originate at a distance from the gap, resulting in a series of peaks and dips in the frequency response known as contour effect or "head bump". The magnetic field generated by the tape, especially at low frequencies, enters the heads from areas not directly over the gap. As the frequencies in the fringing vary, they cancel and reinforce the signal frequencies, thereby producing the peaks and dips. The contour effect is additive as multiple generations of analog recording and playback are performed, so a final stereo mix may show several decibels of low-frequency ripple.

<u>"Thickness" Loss</u> (decrease in output signal due to the thickness of the magnetic medium)

$$L_d \text{ (dB)} = 20 \log [(1-e^{-k\delta})/k\delta]$$

Thickness loss (~16 dB/wavelength distance), not a universally accepted designation, is less severe than spacing loss, but it does indicate that the thickness of the magnetic layer is real and affects the reproduced signal to a measurable degree. The further into the magnetic coating the field penetrates, the less magnetization is retained by the tape since the applied field diminishes with the square of the distance from the gap. In order to determine the overall playback signal amplitude, we must integrate the magnetization through the depth of the magnetic coating. This differs from spacing loss because here the nearest region of the coating is still in contact with the gap, while deeper layers are removed by increasing distance. The magnetic coating thickness for Ampex 456 is about 14 μ, producing about 13 dB of loss for a 19 μ wavelength (20 kHz @ 38 cm/s) sine wave. For high audio frequencies, the thickness of the magnetic coating is the dominant cause of signal loss.

There are many potential sources of distortion in the process of magnetic recording. Changes in both amplitude and frequency may occur that alter the original signal by the time it is played back. These both fall into the category of modulation and have been addressed frequently in the development of the tape recorder. Amplitude modulation (AM) results from changes in amplitude, caused by dropouts or uneven oxide distribution on tape for example. Frequency modulation (FM) results when the frequency of the signal is changed, by tape speed variations caused by poor capstan motor regulation or scraping of the tape against guides or the heads themselves. Both forms of modulation cause frequencies to appear in the signal that were not originally present.

The noise performance of tape recording is dependent on the magnetic material used, the head design and the bias and equalization settings chosen. There are several sources of noise, some of which relate to the physical construction of the medium and some of which relate to the heads and their interaction with the tape. The application of a DC signal to a recording head results in an increase in playback noise of up to 10 dB over the level on blank unrecorded tape. This phenomenon is related to the imperfect distribution of magnetic particle orientation and size. A perfect magnetic medium would have a random distribution of infinitesimal magnetic particles. While this is impossible in real world manufacturing, the minimization of noise is one of the goals of continued research in materials science. Since AC signals can be considered as short sections of DC, the recording of AC signals also generates a noise known as modulation noise. This is clearly audible when recording pure sine waves (calibration tones, for example), as the sine tone fails to fully mask the sideband frequencies generated. With more complex musical signals modulation noise is largely masked by the program.

The physical smoothness of the tape surface determines the amount of asperity noise, which is generated by an uneven tape surface changing the head-to-tape contact. Minute imperfections in the medium surface cause the head-to-tape spacing to change and increase the friction of the contact. The non-uniform distribution of magnetic particle on tape results in a form of noise resulting from flux lines caused by differences in magnetization along the tape even when the applied field is constant. Both of these noise sources can be minimized by reducing the size of the magnetic particles and by reducing the variation in particle size and distribution.

The record head also contributes to noise, as the domains within the head itself react to the imposed magnetic field and restrictions that limit their ability to smoothly align their magnetic polarities, creating what is known as Barkhausen noise. As each domain aligns and joins those already aligned, noise bursts result. By reducing the size of the domains, this noise can be minimized. A further source of noise in record heads results from magnetostriction, mechanical stress changes in the head material due to the magnetic field force on the metal. (This phenomenon also accounts for the hum heard in power transformers.) There's also some noise contributed by the electronic circuitry, particularly the preamplifier required to boost the voltage recovered by the playback head, although this noise is generally significantly lower than the noise from the magnetic medium itself.

Due to the noise inherent in analog recorders, add-on systems have been devised to reduce the noise level. While some such systems use dynamic low-pass filters to separate signal from noise, most noise reduction devices use compression to reduce the input signal's dynamic range and complementary expansion on playback to restore the original dynamics. While these systems work on similar principles, each approaches the problem slightly differently and with varying levels of complexity. Popular music recording often avoids using noise reduction by recording high amplitudes to tape, maximizing the inherent signal-to-noise ratio. Enough engineers prefer the lower noise to encourage the development of very complex multi-band noise reduction systems that make use of masking curves to maximize the noise reduction while minimizing the alteration of the signal. Since each track added to a mix contributes 3 dB of wideband noise, noise reduction is of more importance to multi-track recorders than simpler stereo recorders.

Dbx type I noise reduction uses a single compressor/expander for each channel with a fixed pre-emphasis/de-emphasis filter system. By boosting the high frequencies before recording the signal, the system is able to cut high frequencies a complementary amount on playback, reducing high frequency noise added during the recording process at the same time. This relies on the fact that high frequency components of the signal are usually of low amplitude and the pre-emphasis will not cause clipping. Dolby A uses 4 filter bands, each with a separate compressor and expander. Dolby SR uses both fixed and adaptive filters to split the spectrum into 10 separately processed frequency bands. The issue of recorder calibration becomes important with any of these devices as they rely on system linearity to properly restore the original dynamic range of the signal. Calibration tones should be recorded at the beginning of tapes recorded with noise reduction to allow proper frequency response adjustments to be made later. Improper adjustment of recorder frequency response will result in artifacts created by the noise reduction systems, usually audible gain changes that create a "pumping" effect.

The earliest magnetic recorders were limited to a single channel of audio. Eventually, the ability to fabricate more than one gap in a head assembly opened up the ability to record more than one audio signal at a time. The alignment of the gaps is a critical aspect of the ability to interchange tapes from one machine to another, so the alignment must be very accurate. The ability to create multiple gaps close together makes it possible to record many signals at the same time on the same piece of tape. The real functional breakthrough, however, came when it was realized that the ability to play previously recorded signals and record on other channels at the same time would make the process we know as overdubbing possible. Since the playback head is separated from the record head, signals reproduced from the playback head would not be in synchrony with the signal recorded at the record head. This would result in a time delay between old and new signals on tape. The solution is to allow playback on previously recorded channels through the record head, thereby keeping the playback and record gaps aligned.

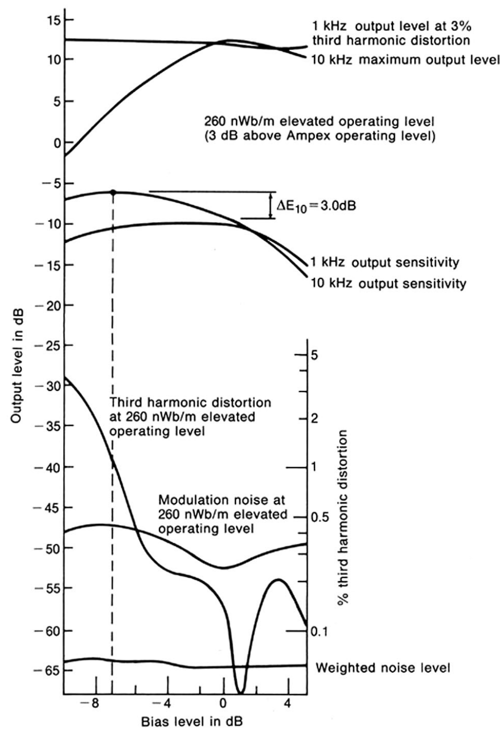
Multi-track recording and synchronous playback/recording go together to allow the ability to add new material to tracks already recorded. Since the record and monitoring playback gaps are the same, the optimization of gap length for recording or playback must be sacrificed to allow both functions through the same gaps. Generally, the playback response through the record head is inferior to that of the dedicated playback head, but the best analog recorders have very good response even through the record head gaps. One problem inherent in overdubbing is the leakage of the record signal into the playback gaps, especially on adjacent tracks. The leakage is caused by the bias radiating from the recording gaps into nearby playback gaps, carrying with it the audio signal. This leakage does not affect the final playback but only the monitoring while overdubbing is under way.

The number of tracks that can be recorded depends on the width of the tape and the gap widths deemed sufficient for the desired signal-to-noise performance, since the recovered signal amplitude depends on the surface area of tape available to generate the magnetic field sensed by the head gaps. Standard reel-to-reel tape widths range from 1/4", 1/2", 1" to 2" for open-reel recorders. Quarter-inch tapes are usually used for stereo (two track) masters, although more tracks can be recorded on quarter-inch tape with reduced performance. Standard professional recorders use wider gaps and can accomplish 24 tracks on 2" tape, although 2" 16-track recorders produce somewhat better sound quality. Recently, 1" two-track mastering machines have been created. At the other end, 8-track 1/4" machines have also been produced. Because magnetic fields radiate into space, adjacent tracks can "bleed" if they are placed close together. This is another consideration in the design of multi-track heads.

Because analog recorders' performance depends on a constant velocity of medium across the heads, the mechanical design of these machines is important. Tape is unwound from the supply reel, pulled across the head assembly, and wound onto the take-up reel. As the reels rotate, the tape is fed from one reel to the other. This results in an increase in the rotation rate of the supply reel and a reduction in the rotation rate of the take-up reel. To keep the rate of tape across the heads constant, a capstan rotates at a constant speed and a pinch roller presses the tape against the capstan. The constancy of the capstan rotation provides a constant tape speed. Advanced designs have used servo control to allow operation without a capstan, but many analog recorders still employ the capstan to provide constant tape speed. If variable speed operation is desired, the capstan rotation rate and the tension applied to the supply and take-up reels can be varied.

Due to the mechanical and electronic adjustments necessary to guarantee the best performance, analog recorders often require maintenance, including the frequent adjustment of critical electrical settings like bias and equalization for each channel and each tape formulation used. Further, since tapes are likely to be exchanged from one machine to another, the physical alignment of the heads needs to be standardized. This is accomplished by the use of standard calibration tapes containing full-track recordings of sine tones at different frequencies to allow electronic and mechanical adjustments. The calibration tape is used to adjust playback and then the record heads and electronics are adjusted to produce a recording that mimics the calibration tape. Generally, calibration tapes are full track, not divided into specific channels. This allows one tape to be used to calibrate all recorders of a specific tape width regardless of how many audio tracks are actually recorded. The drawback to this is that since there is magnetic flux on the tape in what would ordinarily be guard bands between tracks, the low frequency playback signals are larger than they would be if the tape had been recorded on the machine being calibrated. Calibrations must then be adjusted by an amount specified by the manufacturer for low frequency playback. This increase in low frequency signal is due to the fringing effect, where the magnetic field near the gap is sensed by the head.

Adjusting the bias level gives the recordist some options in selecting the balance of noise level, distortion, and high-frequency sensitivity. Each tape formulation has a different set of curves relating these factors to the bias signal level. As may be seen in Figure 6, the amount of third harmonic distortion and the output sensitivity are heavily influenced by the amount of bias signal. The maximum output levels and modulation noise also depend on the bias level. The vertical dotted line indicates the maximum output sensitivity. If we feed a 10kHz sine wave into the recorder and increase the bias level, we will see a peak in the output level indication as we raise the bias level. If we further increase the bias, the output level will begin to decrease. Often the manufacturer will recommend a bias level that produces 3 dB of reduction from the peak, an "overbias" of 3 dB (ΔE_{10} in Fig. 6). The bias adjustment must be made on each channel separately, a rather time-consuming endeavor on a 24 track machine.



(B) Grand Master. (Courtesy Ampex Corp.)

Fig. 6: Ampex 456 tape characteristics (from Ampex Corp.)

To further complicate the calibration process, several different equalization curves have been used in the design of analog recorders. A separate calibration tape is required for each curve and each tape speed. Most manufacturers recommend one of the equalization systems, the main ones being NAB, IEC (CCIR), for use on a particular deck. Often a tape formulation is adopted by a studio and favored as it delivers the sound desired and minimizes the amount of recalibration needed between projects. Some later recorder designs provide automatic calibration, but tedious manual setting of the many EQ and bias settings is more common and usually done by a dedicated technician.

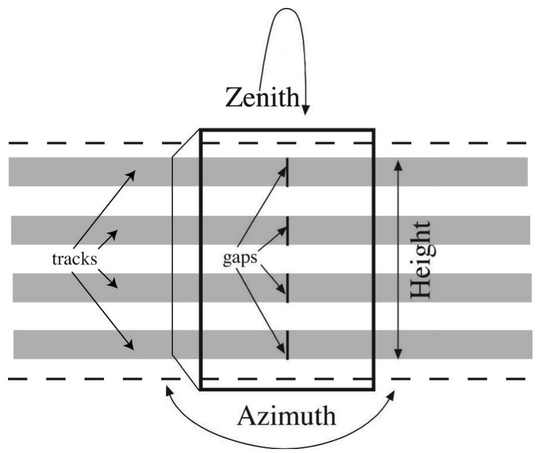


Fig. 7: Head alignments

The three dimensional adjustment of the heads relative to the tape is important. The height and tilt of the heads relative to the tape is adjusted to guarantee the longest head life and best electronic performance possible. The height adjustment determines how the head gaps align vertically with the tape as it is pulled across the heads. The zenith adjustment controls how the heads lean outward: neither the top nor bottom should lean further out so that the heads will wear evenly over time. The alignment most often requiring adjustment is the azimuth, the angle the head gaps make with the longitudinal axis of the tape. If the azimuth is misadjusted, the top and bottom tracks will not be played exactly simultaneously and high frequencies may then cancel when they are just one half cycle out of phase. For 20 kHz sine waves, this amounts to less than a 10 μ difference! Azimuth is adjusted by playing a full track calibration tape while changing the setting until the outermost tracks are in phase at high frequencies. This may be observed on an oscilloscope as an x-y plot of the two outer channels where proper alignment shows a line of slope +1.

So far we have considered analog magnetic recorders. Digital recorders are rapidly displacing analog recorders as the most popular and inexpensive recording devices. Digital recorders convert the analog input signal to a series of sampled, or measured, values that are then stored as a list of numbers. This system is obviously very different from the analog tape recorder, although it ultimately writes a magnetic pattern on a medium not unlike tape. The ubiquity of computers has generated many hardware approaches to using digital recorders to store audio signals, some systems use stand-alone computer hardware to create a recorder and others use personal computers with add-on converters to provide the computer with digitized audio signals. Because these systems are inherently different from analog recorders, we will consider them separately.

Suggested reading:

Handbook for Sound Engineers, 3rd Edition, Glen M Ballou, Ed., Focal Press, 2002. ISBN 0-240-80454-6 [Chapter 28, Magnetic Recording and Playback]

Theory of Magnetic Recording, H. Neal Bertram, Cambridge University Press, 1992. ISBN 0-521-44512-4

Magnetic Recording Handbook, C. Denis Mee and Eric D. Daniel, McGraw-Hill, Inc., 1990. ISBN 0-07-041274-X

Sound Recording Handbook, John N. Woram, Howard W. Sams & Co., 1989. ISBN 0-672-22583-2 [Chapter 9-11.]

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