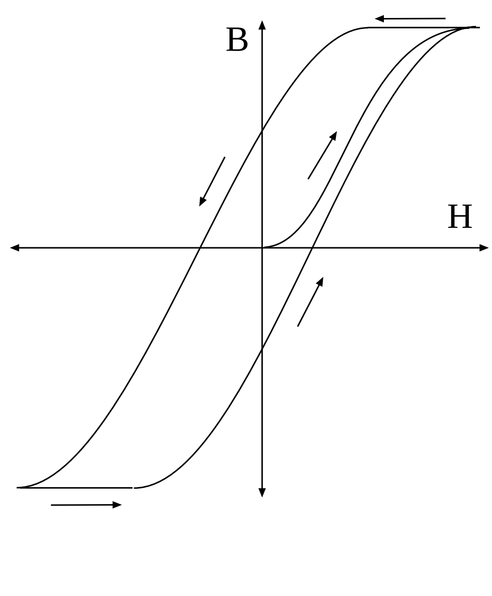
Magnetic Recording Theory

Until recently, there was one dominant way of recording signals so that they could be reproduced at a later time or in a different location: analog magnetic recording (of course, there were mechanical methods like phonograph records, but they could not be easily recorded). In fact, magnetic recording techniques are still the most common way of recording signals. The system relies on the imposition of a magnetic field, derived from an electrical signal, on a magnetically susceptible medium, which becomes magnetized. The magnetic medium employed is magnetic tape: a thin plastic ribbon with randomly oriented microscopic magnetic particles glued to the surface. The record head magnetic field alters the polarization (not the physical orientation) of the tiny particles so that they align their magnetic domains with the imposed field: the stronger the imposed field, the more particles align their orientations with the field, until all of the particles are magnetized. The retained pattern of magnetization stores the representation of the signal. When the magnetized medium is moved past a read head, an electrical signal is produced. Unfortunately, the process is very non-linear, so the resulting playback signal is different from the original signal. Much of the circuitry employed in an analog tape recorder is necessary to undo the non-linear distortion introduced by the physics of the system.

Recording The record head converts an electrical signal into a magnetic field which can be used to create a pattern of magnetization in the tiny magnetic particles of the tape. The head consists of a torroidal core with a small air gap. A coil of wire is wound around the core, which is made of a magnetically permeable metal. Much like a transformer, the record head converts an electrical signal into a changing magnetic field. Since the gap in the head exhibits a high reluctance (the magnetic equivalent of resistance), the field flows through the lower reluctance of the magnetic tape as it moves past the gap. As the tape moves away from the gap, the magnetic flux (the magnetic equivalent of current) decreases as the inverse square of distance. At some distance, it is no longer strong enough to change the magnetic particles on the tape and the magnetization pattern then present is retained. This means that the actual recording takes place at the so-called “trailing edge” of the gap, rather over the entire gap length.



H=applied field   B=retained field

The process of recording information to magnetic polarizations involves the interaction an imposed magnetic field with a magnetizable layer on the tape. The process is not inherently linear: as the imposed recording magnetic field increases it at first has no effect on the magnetic particles. As the field strength increases, it begins to magnetize some particles. For some amount of signal level increase, the magnetization left on the tape increases linearly. At high levels, there are fewer and fewer magnetic particles left to magnetize and the tape becomes saturated until no unmagnetized particles are left. This results in what is called hysteresis: tape magnetic domains are not linearly changed by the imposed signal. This results in distortion of the recorded signal.

Reproduction The reproduce process is conceptually the reverse of the recording process: as the magnetized tape is moved past the reproduce head gap, it's magnetic field induces a flux in the head. This flux then causes a current to flow in the coil of wire which is wrapped around the head core. Unlike the recording head, the length of the reproduce head gap is critically related to the ability of the head to reproduce the frequencies recorded on the tape. This is because the flux generated in the gap is created over the entire gap length rather than at the trailing edge as in the recording process. This means that a recorded signal with a wavelength just equal to the gap length produces no net flux, and is therefore not reproduced at all! Hence there is an inherent high-frequency roll-off as the frequency approaches the gap wavelength. The equation relating the reproduced voltage (V) and the flux seen by the head is:

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

where Φ = average gap flux , t = time , v= velocity, x = position, and 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. Since this rate of change increases with increasing frequency 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 high-pass filter being created. 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.

Definitions

recording field : the magnetic field produced by a record head when current is applied.
Units = A / m or Oe (oersteds): 1 A/m = $4\pi \times 10^{-3}$ Oe

remanence : the amount of field left on tape by recording.
Units = A/m or Oe.

flux : magnetic equivalent of current.
Units = Wb (webers) or Mx (maxwells):1 Wb = 10^8 Mx

flux density : measure of flux per unit area of magnetized material.
Units = T (tesla) = Wb/m^2 or G (gauss) :1 T = 10^4 G

retentivity : a measure of flux remaining after the magnetic field has been removed.
Units = same as flux density.

coercivity : magnetic field strength required to completetly demagnetize a material.
Units = same as recording field.

Analog versus digital: There are two approaches to recording audio information onto magnetic tape: analog and digital. Analog magnetic recording takes the electronic signal and creates a magnetic field proportional to the voltage of the signal. This magnetic signal is then used to magnetize a strip of plastic film onto which has been glued a coating of magnetic particles. As the tape moves past the record head, it magnetizes the particles on the tape, leaving a magnetic field as the tape moves away from the head. This tape, when pulled past a playback head, reproduces the original electronic signal at the output of the reproduce head.

For analog recording, in addition to the signal we wish to record, a high frequency signal is mixed in before the signals are sent to the record head. This high frequency signal is called a "bias" signal. It's frequency can vary from 75 kHz to over 200 kHz, well above the range of audibility. The bias signal is mixed linearly with the audio signal, it is not amplitude-modulated. It can, therefore, simply be filtered out in the process of reproduction. The circuit that does this filtering is known as a bias trap. The purpose of the bias signal is to overcome the inherently non-linear relationship between the imposed magnetic field and the flux retained by the tape, greatly reducing the distortion. At low signal levels, the magnetic field is too weak to begin magnetizing the particles and no signal is recorded. As the signal increases, the particles begin to become magnetized. By adding AC bias to the signal, the magnetic field is increased even for the low-level audio signals and undistorted recording is possible.

Digital magnetic recording is different in that the electronic signal is first measured and converted into numbers which describe the signal voltage at a particular time. The numbers are processed and then written as binary data, which is recorded to the magnetic tape as magnetic polarizations of two distinct polarities which code for 1s and 0s. The processing of signals for conversion to digital representation is quite complicated and will be investigated at length later. Because digital magnetic recording uses only two states, it does not require the use of bias current to reduce the zero-crossing distortion encountered in analog linear magnetic recording. It does, however, require plenty of signal conditioning in order to make the accuracy of the process acceptable.

Analog Tape Recorders

The process of analog magnetic recording, while conceptually simple, is full of technical compromises due to the complicated physics of the process of transferring magnetic energy from the tape head to the tape and back again. The physics of recording is quite different from the physics of the playback process, thus a different set of trade-offs is presented by each. The overall process must allow the transfer of audio information with a minimum of distortion and added noise. We will look at some of the imperfections of the analog magnetic recording process in detail.

The Record Head

As discussed previously, the actual recording occurs at the trailing edge of the record head as the imposed magnetic field begins to fall off with the square of the distance from the gap. When the recording field strength falls below the coercivity of the tape, the signal is permanently recorded. This occurs at a finite distance from the gap. In fact, the effective gap length at the record head is about 14% larger than the physical gap length because the magnetic field spreads out in space. This spread can also result in crosstalk between adjacent channels when the record head is used for both recording and playback in the process of overdubbing.

Bias Current: The recording process is complicated by the need for a bias current to reduce the non-linear effects of magnetic tape's hysteresis. This hysteresis is a result of the fact that the magnetic domains of the tape magnetic coating have a minimum applied field strength (threshold) below which they are not able to be magnetized, so low-amplitude audio signals cannot be transferred to tape magnetization. By mixing a high-frequency sine wave with the audio signal, the resultant signal amplitude keeps the recording head magnetic field magnitude large enough to avoid the dead-band region of the transfer curve. Since the bias signal is much higher in frequency that the audio signal and is mixed in linearly, it can be removed with a simple filter, the bias trap. Also, due to its high frequency, the bias signal is not efficiently read by the playback heads. The use of bias current dramatically reduces the distortion of the recording stage. By adjusting the amount of bias current added, a balance between distortion and frequency response can be chosen in the record alignment process.

Self Erasure: One kind of high frequency loss that takes place at the record head is self-erasure. This phenomenon takes place as the magnetized tape leaves the gap area. A secondary (or phantom) gap is created between the record head and the newly-magnetized tape. This gap field tends to erase the high-frequencies on the tape. It is made worse if the head is magnetized, so we must be careful to demagnetize the heads regularly.

Recording Head Gaps: The length of the recording head gap is chosen to allow the magnetic field to optimally penetrate the magnetic coating: the gap is generally about equal to the thickness of the magnetic coating. (Record head gaps range from 2.5 to 12 microns.)

A special record head is used to erase the tape before a new recording is made. The erase head has a larger gap length, since it must completely demagnetize the entire thickness of the tape to remove any remaining signal. The gap length used in erase heads can be 3 to 4 times the thickness of the magnetic layer. Pure bias current is used to remove any remanent magnetization from the tape and randomly magnetize the particles. (Erase head gaps range from 25 to 125 microns.)

The Reproduce Head

The equation describing the reproduce head relationship for a sine-wave signal 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

- $e(x)$ = 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 = wavenumber ($= 2\pi / \lambda$) where λ = wavelength
- δ = thickness of the magnetic medium
- d = distance from tape to head

The terms in square brackets are loss terms relating to specific physical relationships which act to reduce the output voltage at the reproduce head:

Spacing Loss (decrease in output signal due to distance from tape to head):

$L_d = e^{-kd}$

Spacing loss increases exponentially with increasing distance as a ratio of the wavelength of the signal, thus high frequencies are more susceptible to dropouts. (Spacing loss can be expressed as 54.6 dB / wavelength distance, meaning that almost 60 dB of dropout is produced if the tape is separated from the head by the wavelength of the signal of interest!)

Gap Loss (decrease in output signal due to the length of the gap)

$L_g = \sin(kg/2)/(kg/2)$

Gap loss reflects the fact that the reproduce head responds to the average flux in the gap: therefore, if the wavelength of the signal just equals the gap length, there is no signal produced. At low frequencies, this also results in a series of peaks and dips in the frequency response known as “head bump”.

Thickness Loss (decrease in output signal due to the thickness of the magnetic medium)

$L_d = (1-e^{-k\delta})/k\delta$

Thickness loss is not as severe as spacing loss, but it does indicate that the thickness of the magnetic layer is real and does affect the output signal to a measureable degree.

Reproduce Head Gaps: The gap length of the reproduce head must be optimized to allow the greatest signal recovery without compromising the highest frequency (shortest wavelength) that we need to preserve. Reproduce head gaps are the smallest of the three types of heads: the average output level is compromised somewhat to allow higher frequencies to be reproduced. The reproduce head gap length is more critical than are record head gap lengths. (Reproduce head gaps range from 1.5 to 6 microns.)

Equalization

Because the process of recording and reproducing signals on magnetic tape is a frequency-dependent process, equalization is used to restore flat frequency response within the limits imposed by the physical processes already discussed.

Since reproducing a tape recording is a differentiating process, there is a 6 dB / octave rise in the amplitude of the recorded and reproduced signal. Equalization can be applied during the record process and during the reproduce process to correct the resultant frequency response. It is desirable to boost frequencies during record, since this allows us to cut frequencies during playback, however we must be careful not to boost frequencies enough to cause tape saturation. Since the signal at playback contains noise and distortion produced by the recording process, filtering (cutting some frequencies) during playback provides a way of reducing the unwanted components: they are filtered out by the post-equalization.