Introduction to Analog Audio Tape Recording: A Paper Discussing The Basic Physical and Electrical Process by Which Sound is Recorded Onto Analog Magnetic Tape

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Simplistic Recording Concepts

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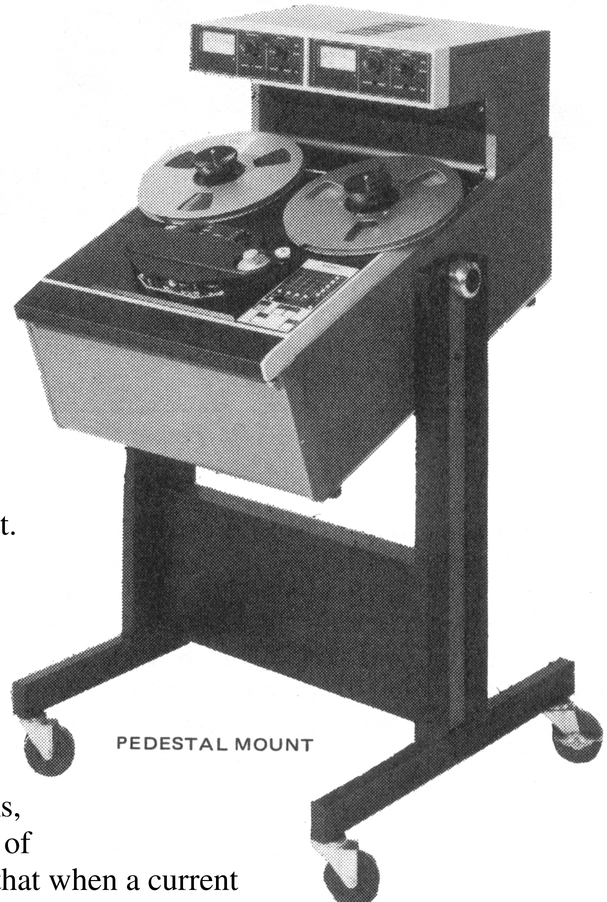


Analog tape recording and reproduction is a relatively simple concept. It relies heavily on the Oersted effect. This paper will discuss, the basic operating principals of large format (open reel) analog tape recording and reproduction. This paper will not discuss low speed, small format (cassette) recording. The Ampex ATR-102 will be used as the "model" tape recorder in this paper. I chose this machine, because I own it and I have a lot of documentation on it.

(Photo at the right, from Ampex ATR-102 Operation and Service manual.)

Section 1: Review of the Oersted Effect:

In order to properly understand how analog tape recording and reproduction works, we must first have a complete understanding of the Oersted effect. The Oersted effect states that when a current passes through a wire, lines of magnetism are generated. These lines of magnetism are called lines of flux. This also works in reverse. If a magnet is passed through a coil, a current is generated in the wire. As we will find out later, this is the basic operating principal of the recording head, and the reproduce head, used in magnetic tape recording.

Section 2: Parts of a magnetic tape recorder:

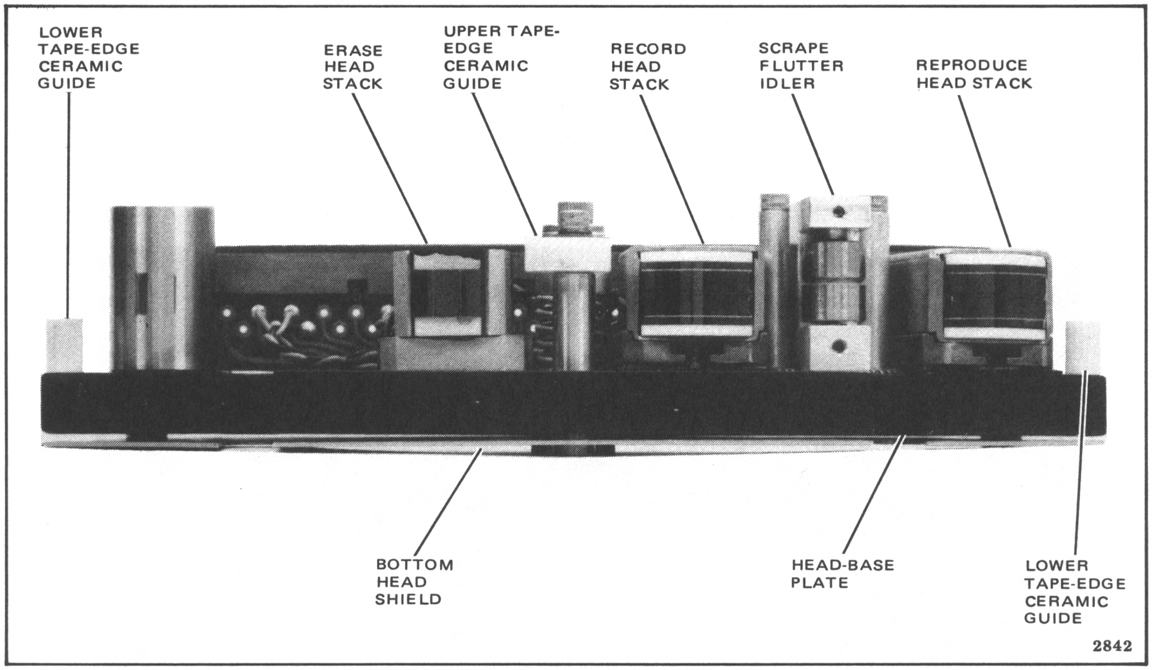
Most analog tape recorders consist of seven major parts (excluding the power supply):

1.) Transport
2.) Head block assembly
3.) Input/output modules
4.) VU meters
5.) Record amplifiers and equalizers
6.) Bias oscillator and amplifier
7.) Reproduction (repro) amplifiers and equalizers

Section 2.1: The transport and head block assembly:

The transport is the mechanism which moves the tape past the heads. It is crucial that the transport be aligned with absolute precision. If the transport guides are even slightly misaligned, the tape will encounter unwanted friction, causing audible wow and flutter in the recording and playback. In worst case, the tape may not come in contact with the head properly, causing phase shifts in the output signal. The transport works very closely with the head block assembly, and the guides which it contains. The job of the transport is to move the tape across the heads, while maintaining uniform tape to head contact, and alignment. The head block assembly contains three heads that are always in the following order:

Erase head
Record head
Reproduce (repro) head



Ampex ATR-102 (quarter inch tape) headblock assembly. Picture from Ampex ATR-102 Operation and Service manual.

Each head is mounted on a rigid base plate, which is connected to a tapered gear. This allows us to easily adjust the azimuth of each head. Most headblocks will allow you to adjust both the azimuth and zenith of each head. However, the Ampex ATR top mounting plate and headblock is machined with such precision, that a zenith adjustment is not necessary. Alignment is very solid on this machine. Once azimuth is properly set, it rarely needs adjustment. The only time that an adjustment may be required is if a tape from an improperly aligned machine is played on the ATR, or headblocks are swapped out. The electrical connection between the headblock and the tape machine is made by way of a multi-pin connector at the base of the headblock, which mates with the corresponding female socket on the ATR's top plate. Once the electrical connection has been made, using an Allen wrench, a spring loaded bolt is rotated causing the headblock assembly to be firmly locked in place, assuring that alignment is preserved.

Section 2.2: Input/output modules:

The function of the input output modules is just as their name states. They bring signals to the record electronics, and signals out of the repro electronics. Most professional tape machines will have balanced female XLR type inputs, and balanced male XLR type outputs. On a rare occasion, a machine might have TRS balanced quarter inch inputs and outputs, or even unbalanced RCA coaxial type inputs and outputs. A stock Ampex ATR-102 has transformer balanced XLR type inputs and outputs. A word of caution, on an unmodified stock ATR, pin 2 is NOT hi, pin 3 is. The pin configuration is clearly stated on the rear of the I/O main frame assembly. The ATR was designed and built in the late 1970's and early 1980's, before "pin 2 hi" was made the standard for XLR type connectors.

Section 2.3: VU Meters:

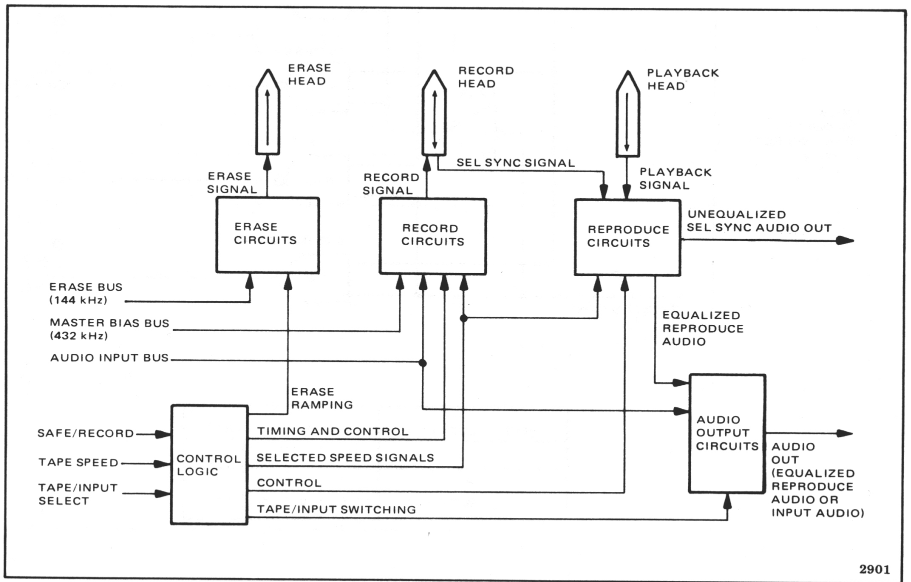
Also contained in the I/O module, is the VU meter. The VU meter displays the input signal in dBu (ref. .775 volts), and the output of the repro amplifier in dBu, relative to the flux level (in nano-webers per meter nWb/m) recorded on the tape. On a machine set up for standard, elevated level tape, 250 nWb/m will equal 0 dB on the VU meter. However you should never assume that a machine is calibrated in this way. Always reproduce a calibration tape, recorded with a known relative flux level, and set the meters accordingly. If you have a 250 nWb/m calibration tape, and you wish to use media with a relative flux level of 250 nWb/m, set the output so that the meter reads "0 dB". If you want to use tape with a relative flux level of 355 nWb/m, which yields an output of +6 dB, reproduce the 250 nWb/m test tape, and set the output so that the meter reads "-3 dB". This way, the entire range of the tape is visible on the meter. The levels on the meter have shifted as follows: -3 dB on meter= 0 dB output, 0 dB= +3 dB, and +3 dB= +6 dB.

Section 2.4: Record amplifiers and equalizers:

The record amplifiers and equalizers prepare the signal received at the inputs for recording. Here, the signal is strengthened to the point that when the signal reaches the recording head, it will create enough magnetic flux to overcome the corrective force of the magnetic particles on the tape, and create the recording. The recording amplifier has variable gain, which can be adjusted. Once the repro output has been calibrated (with a test tape) the record gain can be adjusted, so that a 0 dB input = a 0 dB output (or any output, if desired).

The recording equalizer places the equalization curve being used (NAB or IEC for 7.5ips and 15ips, and AES for 30ips) on the recording. Pre emphasis must be used in order to lower the noise floor of the tape. Tape hiss, and EQ curves will be discussed later.

Section 2.5: Bias oscillator and amplifier:



The bias circuit creates a very high frequency tone, which helps to excite the magnetic particles resulting in wider frequency response, and significantly lower distortion figures. In the Ampex ATR-102, the bias frequency is 432 KHz. This high frequency tone is obviously not audible, nor is it actually It is simply used to excite the magnetic particles.

(The drawing above is a simplified block diagram of the Ampex ATR-102. Drawing from the Ampex ATR-102 Operation and Service manual.)

Section 2.6: Reproduce (repro) amplifiers and equalizers:

The reproduce amplifiers boost the small signal created by the head, into line level signals. The equalizers reverse the EQ placed on the tape during recording. However, these equalizers are not preset like the ones in the record circuit. There is an EQ adjustment for high and low frequencies, and the shelving characteristics of these filters. This is to compensate for the different characteristics of each type of tape. In the Ampex ATR-102, this is called the Parameter Determining Network, or PADNET. On the rear of this board is a multi-pin connector that mates with the corresponding female socket on the audio printed wiring assembly (PWA).

Section 3: Analog magnetic tape recording and reproduction: The process:

Now that we understand the basic parts of the tape machine, we can begin to put those parts together, and see how they work to create the final recording.

Section 3.1: Erase head

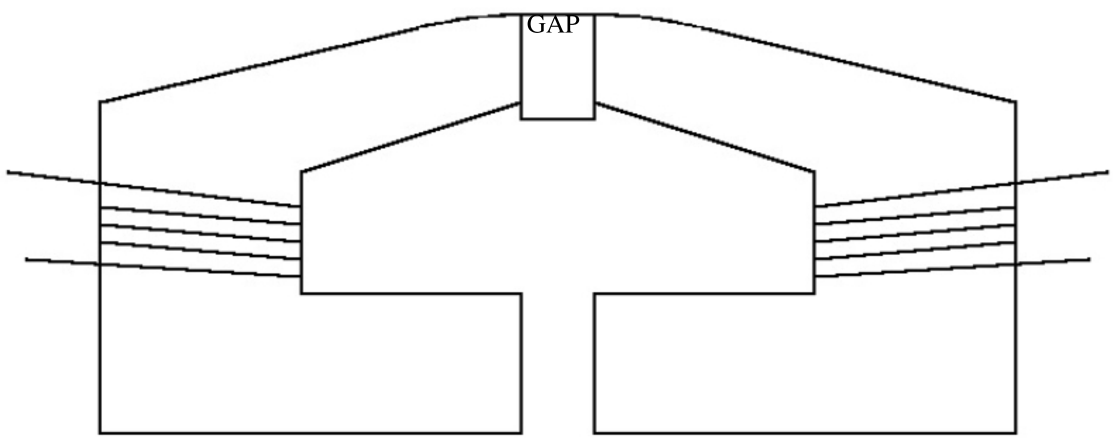
The erase head is the first head in the headblock assembly. It demagnetizes the tape, erasing whatever was previously stored on the tape, making it easier for the record head to magnetize the tape. High frequency AC current is used to demagnetize the tape. In the Ampex ATR-102 a 144 KHz AC current travels from the master oscillator to the erase amplifier and then to the erase head. This high speed alternating current, when fed through the coils of the erase head, create a very strong alternating magnetic field. When this alternating field comes in contact with the magnetic tape, the particles on the tape are scattered at random, some particles facing north, some south and some in between. The tape contains little or no signal at all. However, there is some signal on the tape. Each particle on the tape is a magnet that has a field strength that decreases as the inverse cube to square of the distance. This field is sensed by the repro head. The random noise voltage will increase proportional to the square root of their number n per volume unit:

$$E_{noise} = K * \sqrt{n}$$

Where K is the proportionality factor.

Section 3.2: The Record head:

The record head is very similar to the erase head. When a current is passed through its coils, lines of magnetic flux are generated in the gap. When the field strength generated in the gap (in nWb), reaches and exceeds the corrective force of the particular tape in use, the magnetic particles on the tape become arranged in a pattern analogous to the original waveform that traveled through the air, into the microphone.



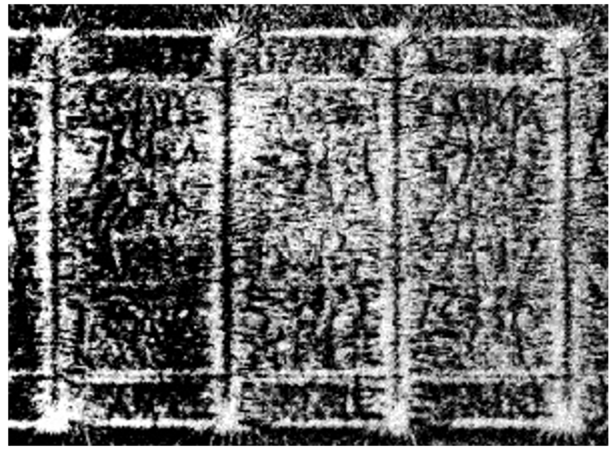
Drawing by Joseph Nino-Hernes

We can determine the value of Hg, the magnetic field inside the gap, using the following formula:

$$H_x(x, y) = \frac{Hg}{\pi}\left\{a\tan\frac{L/2+x}{y} + a\tan\frac{L/2-x}{y}\right\}$$

$$H_y(x, y) = -\frac{Hg}{2\pi}\log_e\left\{\frac{(x+L/2)^2+y^2}{(x-L/2)^2+y^2}\right\}$$

Magnetic recording is not horizontal, like you might think. It is actually vertical. Up represents north, and down represents south, or positive and negative. If we dip a strip of recorded magnetic tape into a mixture of carbonyl iron and heptane, we can easily see the waveform. The heptane quickly evaporates, leaving the iron particles behind in the regions of the tape that were most strongly magnetized. The picture at the right, shows a section of tape. Recorded on the tape at 7.5ips, full track mono, is a 75 Hz note. Inexpensive, noisy tape was used, to show modulation noise. If you look closely, the particles between the recorded poles are scattered all about, and not arranged in any particular pattern. This is modulation noise. The little fringes at the edges of the poles is called fringing. You can also spot lamination defects on this strip of tape. The photo above was reprinted from 3M's Sound Talk bulletin, 1949.



Section 3.3 Reproduce head:

The reproduce head is very much like a record head in reverse. As the magnetized particles pass through the gap, a small current is generated in the coil of the repro head. This current travels from the repro head, to the repro amplifiers. Below is the general playback formula. The first portion of the formula can be used to find the peak reproduce voltage. The last four terms of the equation are losses. This formula assumes that the magnetization pattern is sinusoidal, longitudinal, and uniform through the thickness of the tape.

$$e = e_{peak} * \cos \omega t * losses \mu V$$

$$= n * \psi_m * w * 10^{-3} * \eta p * (2\pi v / \lambda) * \cos(2\pi v t / \lambda)$$

$$* e^{-(2\pi d / \lambda)} * \frac{1 - e^{-(2\pi c' / \lambda)}}{2\pi c' / \lambda)} * \frac{\sin 6}{6} * \frac{\sin x}{6}$$

Where:

n = number of turns	λ = wavelength in meters
ψm = peak flux in nWb/m	d = head-to-coating distance in meters
w = track width in meters	C^1 = recorded thickness in meters
ηp = head efficiency (fraction)	G = $\pi L / \lambda$
v = head-to-coating speed in m/s	X = $(\pi w - \tan \beta) / \lambda$
L = gap length in meters	β = misalignment angle

Conclusion:

Analog magnetic tape recording is a wonderful way to capture sound. It is a relatively simple, electro-physical process, which contributes to its fantastic sonic qualities. Analog tape is also a wonderful archival medium. Reels of Scotch 111 tape that are over 50 years old can be played with no problem. Even the most problematic of tape formulations, like Ampex 456 and Scotch 226, can be played by simply "baking" them in the oven at 135 degrees (F). For quarter inch tape, on a standard 10.5 inch metal reel, bake for 2-4 hours, flipping every half hour. This can not be said for digital hard disk drives. They generally have a lifespan of approximately 10 years. Much like analog tape, each time the read/write head of the hard disk touches the magnetic disk, magnetic particles are worn away. This wear causes errors on the disk. If enough of these errors build up, the file system can become corrupted, causing what data is left on the disk, to become un-readable. Analog tape, on the other hand, can be played back hundreds of times, with little to no noticeable degradation in audio fidelity. The speed of the tape, compared to the rotational speed of a hard disk platter, is relatively slow (7.5ips through 30ips), therefore it does not wear as quickly as a hard disk. Most hard disks today rotate at a speed of at least 7200 rpm. The friction between the read/write head and the magnetic platter is incredible! Place your hand on your hard drive after it has been running hard for an hour or so, it is hot to the touch! The temperature at the read/write head! It is easily in the hundreds of degrees. That characteristic "grinding" noise that your hard disk drive emits, is the read/write head, in contact with the platter. In 10 years, today's engineers who worship digital, will be sorry that they ever placed their precious recordings onto a hard disk drive. Data recovery is very expensive, and it does not have a very high success rate. Also, if there is physical damage to the disk platters, this can not be repaired. Hard disk platters are very similar to analog tape, in that they are coated with a magnetic emulsion. If the binder in this emulsion breaks down, the platter becomes sticky. The problem is, there is no way to monitor this. By the time the read/write head comes in contact with the deteriorated platter, it is too late and the data is destroyed. However, with analog tape, if it is an unstable formulation, it can be monitored. Simply take a few inches of the tape at the beginning or end, where there is no recording, and wipe it a few times with a soft cloth. If the cloth is clean, it is safe to store the tape again. If oxide is on the cloth, then it needs to be baked before the next play. Think again before you archive on hard disk. Think of the future. Analog tape has been around since the 1940's. The technology has improved dramatically, and withstood the test of time. Can the same thing be said about computers…a resounding NO! In 10 years, there might not even be a computer that can read drives of today, and the poor manufacturing quality of computers today, will prevent them from being operational 10 years from now. However, an Ampex tape machine is "forever". Machines that are 30 and 40 years old, still work flawlessly. I can only hope that the industry realizes this before it is too late.

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