APPLICATION NOTE 89

MAGNETIC TAPE RECORDING HANDBOOK

HEWLETT hp PACKARD
(CANADA) LTD

SAN DIEGO, CALIFORNIA, USA

PRINTED: AUGUST 1967

REPRINTED: NOVEMBER 1970
REVISED: OCTOBER 1975

CONTENTS

INTRODUCTION

MAGNETIC RECORDING

TAPE RECORDER HEADS

TAPE TRANSPORT MECHANISMS

ELECTRONICS

MAGNETIC TAPE

SPECIAL TECHNIQUES AND MISCELLANEOUS INFORMATION

CONTENTS (Continued)

ITS STANDARDS

PACKARD INSTRUMENTATION MAGNETIC TAPE RECORDING SYSTEMS

ILLUSTRATIONS

TABLES

INTRODUCTION

INTRODUCTION

1.1 WHY THIS HANDBOOK AND WHAT'S IN IT.

Throughout the world there are many data gathering systems that rely on magnetic tape for data storage. The equipment found in these systems will vary, but they usually contain antennas, receivers, miscellaneous sensors, displays, and tape recorders. The tape recorders are often the most critical units in the system, since to a large extent the success of an operation is measured by the quality of the recorded data.

Except for the tape recorders, the performance of all devices can be measured and calibrated with the use of readily available test equipment and well-understood techniques. Quantitative results from preoperation tests will vouch for the equipment's readiness. But, unfortunately, there is no simple quantitative measurement of a recorder's performance. This situation is further aggravated by the fact that operating and maintenance people are usually not concerned with data analysis and unfortunately do not get immediate feedback on the quality of the tapes. As a result, maintenance priority is often given to other units in the system when routine maintenance to a tape recorder would significantly improve the quality of data for the entire operation.

The purpose of this handbook is to give those people concerned with operation and maintenance of tape recorders a better understanding of the theories and techniques of magnetic recording. Only a very few undergraduate engineering curricula include basic magnetic recording theory, and perhaps the material here can help shed some light in this area. In addition, some practical considerations are offered relating to the application and limitations of the direct and FM recording processes. These considerations should be of value to the system designer in adapting magnetic recording to his system requirements.

1.2 HOW IT ALL BEGAN.

Magnetic recording of information began with Valdemar Poulsen and his "Telegraphon" in 1893 in Denmark, although the basic idea was documented but apparently not built in 1888 by Oberlin Smith, an American. Since that time, great strides in the technology of materials, techniques of manufacture, and a constantly increasing need to record and store information have produced the highly complex magnetic tape recorders of today. As originally conceived, the recorder used steel wire spirally wound on a drum where a stationary transducer recorded or reproduced variations in magnetic flux into or from the wire as the drum rotated. Developments in magnetic materials and processes using steel ribbon tape, especially in Germany during the 1920–1930 era, resulted in several machines similar to present day configurations. In 1935, the first plastic tape was introduced by a recorder manufacturer, AEG of Germany. Tape recorders made in the United States used steel ribbon tape until just after World War II. "Liberation" of several German-made tape recorders by the Allied Forces at the end of the war accounted for the beginning of magnetic tape recording as we know it today in the United States.

In spite of the difficulties in its use, wire recording had a pretty good foothold in this country by the end of World War II, where it was used in home entertainment, in the business world, and by the armed forces. By 1950, however, the many advantages of tape over wire were widely accepted and wire recording became a thing of the past.

Following 1950, great improvements were made in audio recorder technology, and by 1955 stereo recorders were available for home use. In the same period, instrumentation recorders moved up to 60-ips operation, 14 tracks on 1-inch tape, and 100-kHz response. By 1957, television recorders were on the market, and by 1959 instrumentation recorders were capable of 1-MHz response at 120-ips. In 1966, home television recorders were available and instrumentation machines capable of 1-MHz at 60-ips were being built. During the next nine years marked improvements were made in signal to noise ratio and flutter specifications. Todays instruments exceed 2-MHz response at 60-ips while incorporating these improvements.

An integral part of the growth in tape recorder capabilities has been the great strides made in tape technology. From the paper-backed tapes of 1948 to the tensilized polyester tapes of today, many improvements have been made. Oxides, binder formulas, base materials, processing techniques, and exacting quality control standards have been combined to produce the high-resolution extremely smooth instrumentation computer and audio tapes in use today – all exhibiting many times the storage capacity available 25 years ago.

Today's magnetic recorders are capable of many orders of magnitude better performance than the 1893 models, but they still use the same basic magnetic principles; only the materials, techniques and requirements have changed over the years.

1.3 IRIG AND ITS STANDARDS.

A standard in the field of telemetry for guided missiles was established in 1948 by the Committee on Guided Missiles of the Research and Development Board (RDB), Department of Defense, and was thereafter revised and extended as a result of periodic reviews of the standard by the committee's working group on Telemetering of the Panel on Test Range Instrumentation. The last official RDB revision of the standards was published as RDB report MTRI 204/6, dated 8 November 1951. Since the termination of the Research and Development Board, new standards have been prepared by the Inter-Range Instrumentation Group (IRIG). The steering committee representing IRIG and the Department of Defense test ranges has assigned the task of promulgating new or revised telemetry standards to the Telemetry Working Group (TWG). The importance of magnetic tape recording to range instrumentation and its widespread use in telemetry operations long ago led to its inclusion in these standards. IRIG Telemetry Standards, document number 106-73, dated May 1973 represents the latest such standard document and is referenced throughout this handbook simply as IRIG 106-73.* Copies of the document may be obtained from the Defense Documentation Center for Scientific and Technical Information, Cameron Station, Alexandria, Virginia (22314), by ordering AD-780-868. Any applicable tables on IRIG specifications referenced in this document are contained in Appendix A.

*NOTE

At the time of revision Application Note 89, IRIG Telemetry Standards Document 106-73 supersedes 106-71. However, it is most likely that IRIG will reissue their document, in 1975 as "106-75".

Although changes have been made to various articles of the IRIG document, none of the changes seriously affect the information presented in this brochure.

MAGNETIC RECORDING

MAGNETIC RECORDING

The following are three basic elements required to make a magnetic recording and later reproduce it:

1. A device which can respond to an electrical signal and create a magnetic pattern in a magnetizable medium.
2. A magnetizable medium which will conform to and retain the magnetic pattern.
3. A device which can detect such a magnetic pattern and convert it once again to the original electrical signal.

These three elements take the physical form of the record head, the magnetic tape, and the reproduce head. Add some electronic amplification and a mechanical tape handler, and a basic magnetic recorder results.

2.1 DIRECT RECORD/REPRODUCE.

A record head is similar to a transformer with a single winding. Signal current flows in the winding, producing a magnetic flux in the core material. To perform as a record head, the core is made in the form of a closed ring, but unlike a transformer core, the ring has a short nonmagnetic gap in it. When the nonmagnetic gap is bridged by magnetic tape, the flux detours around the gap through the tape completing the magnetic path through the core material. Magnetic tape is simply a ribbon of plastic on which tiny particles of magnetic material have been uniformly deposited. When the tape is moved across the record head gap, the magnetic material, or oxide, is subjected to a flux pattern which is proportional to the signal current in the head winding. As it leaves the head gap, each tiny particle retains the state of magnetization that was last imposed on it by the protruding flux. Thus, the actual recording takes place at the trailing edge of the record head gap. A simplified diagram of the recording process is shown in Figure 1.

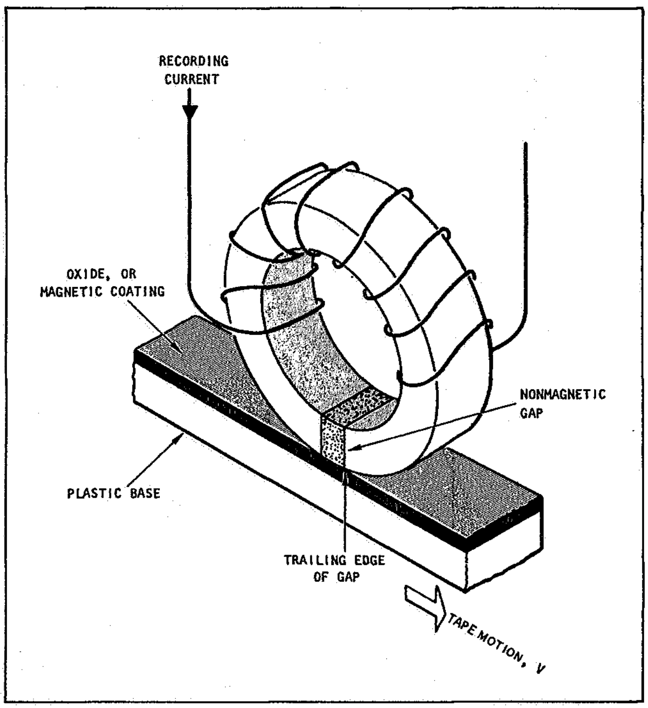


Figure 1. Simplified Diagram of the Magnetic Recording Process

To reproduce the signal, the magnetic pattern on the tape is moved across a reproduce head. Again a small nonmagnetic gap in the head core is bridged by the magnetic oxide of the tape. Magnetic lines of flux are shunted through the core, and are proportional to the magnetic gradient of the pattern on the tape which is spanned by the gap. At this point analysis of the reproduce function is divided into two possible alternatives, i.e., the use of current or voltage amplifiers in the reproduce electronics. Each method will be treated separately, but both will use the same example to allow for easier comparison.

Suppose the signal to be recorded on the tape is a sinewave voltage described by A sin (ωt). Both the current in the record head winding and the flux, ϕ, through the record head core will be proportional to this voltage.

VOLTAGE AMPLIFIER: The induced voltage in the head winding follows the law of electromagnetic induction: $e_s = N \, d\phi \, / \, dt$. It is important to note that the reproduced voltage is not proportional to the magnitude of the flux, but to its rate of change (see Figure 2). If the tape retains this flux pattern and regenerates it in the reproduce head core, the voltage in the reproduce head winding will be

$$e_{repro} \propto \frac{d\phi}{dt}$$

where

$$\frac{d\phi}{dt} = \frac{d}{dt} A \sin(\omega t)$$

$$= \omega A \cos(\omega t).$$

Thus the reproduce head acts as a differentiator and the reproduced signal is actually the derivative of the recorded signal and not the signal itself. This fact imposes two well-known limitations on the direct reproduce process. The output of the reproduce head is proportional to the signal frequency, and to maintain amplitude fidelity, a 6-db-per-octave rise in the head output must be compensated for in the reproduce amplifier by a process known as equalization.

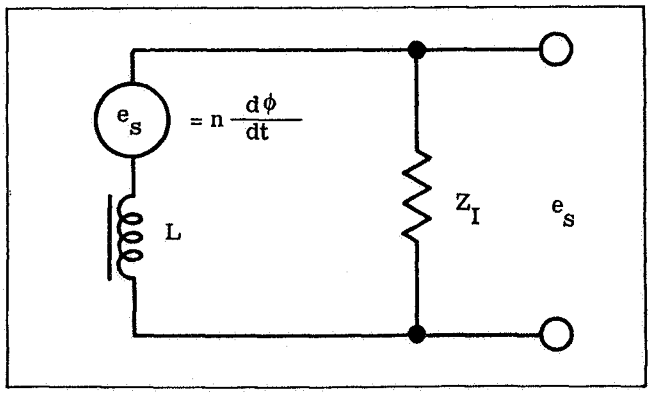


Figure 2. Voltage Equivalent Head Model

CURRENT AMPLIFIER: The induced current in the head winding will follow the equation $i_s = n\phi/L$ (see Figure 3). The corresponding current in the reproduce head winding will be

$$i_{repro} \propto \frac{\phi}{L}$$

where $\phi = A \sin(\omega t)$.

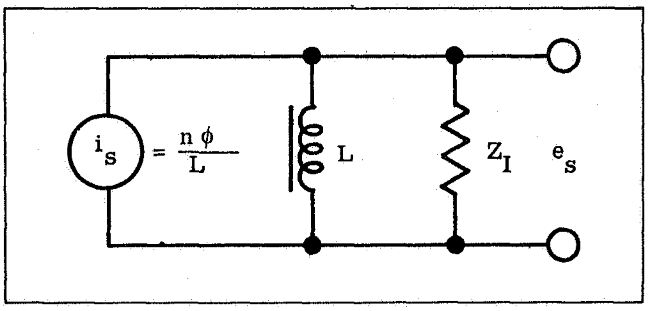


Figure 3. Current Equivalent Head Model

Since this eliminates the 6 db per octave rise in the head output (see Figure 4), the required equalization circuitry need only compensate for the normal high frequency losses (paragraph 2.1.2) encountered in tape recording. The resultant signal attenuation is much greater for the short wavelengths (high frequencies) but is flat for the lower frequencies. An L-C boost circuit after the preamplifier can be employed in the higher frequency regions to, in effect, duplicate the voltage head circuit and thus make the two systems equivalent. A slight gain in signal level is attained in the current model because we have eliminated attenuation of the higher frequencies due to head losses.

An overall comparison would yield the following data on current amplifiers:

1. The output is independent of tape speed.

2. The bandwidth limitation of signals by the input capacity is reduced.

3. The effect of head losses on signal amplitude is minimized.

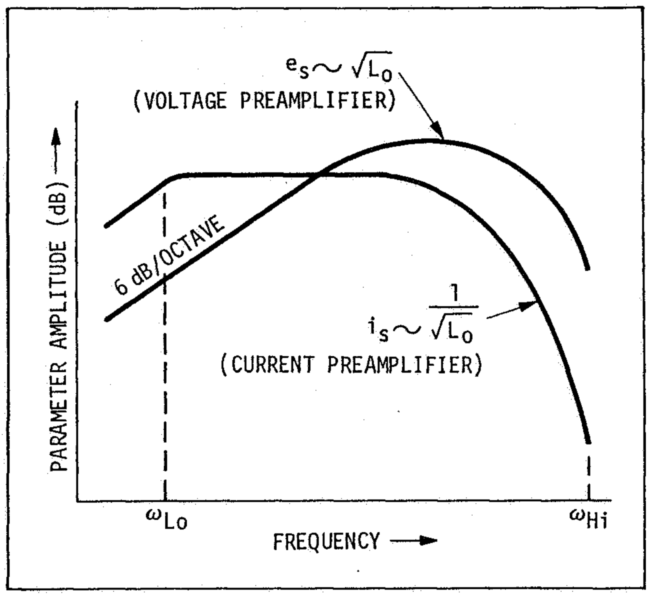


Figure 4. I Vs. V Curves

4. The effect of head inductance variations on high frequency signals is removed.

5. Although the S/N characteristics of both the current and voltage amplifiers are the same, high Q leads may be used with the current amplifiers to achieve higher S/N ratios.

For both types of amplification another limitation occurs as the recorded frequency approaches zero. At some point the output voltage from the reproduce head falls below the inherent noise level of the overall recording system. So, there is a low-frequency limit in the direct record process, below which reproduction cannot be made.

2.1.1 BIAS.

Up to now our discussion has assumed that the magnetizable medium responds linearly to the magnetizing force of the record head. As might be expected, the perversity of nature asserts itself and the assumption is in error. Like other magnetic materials, the particles on the tape exhibit a very nonlinear characteristic when exposed to a magnetizing force. A typical magnetization curve, or hysteresis loop, is shown in Figure 5.

H is the magnetizing force and is determined by the number of turns and the current in the record head winding. B is the resultant induced magnetization on the tape.

As a demagnetized particle on the tape approaches the record head gap, it carries no residual magnetism. (Point 0, at the origin, Figure 5). Assuming that a cycle of the recorded signal along the tape is very long compared to the gap length, the particle will pass through an essentially constant magnetizing force created by the recording current. Referring to the curve of Figure 5, such a force, (H_R), will carry the particle up the curve OA to point R, at the center of the gap. As the particle leaves the gap, H falls to zero,

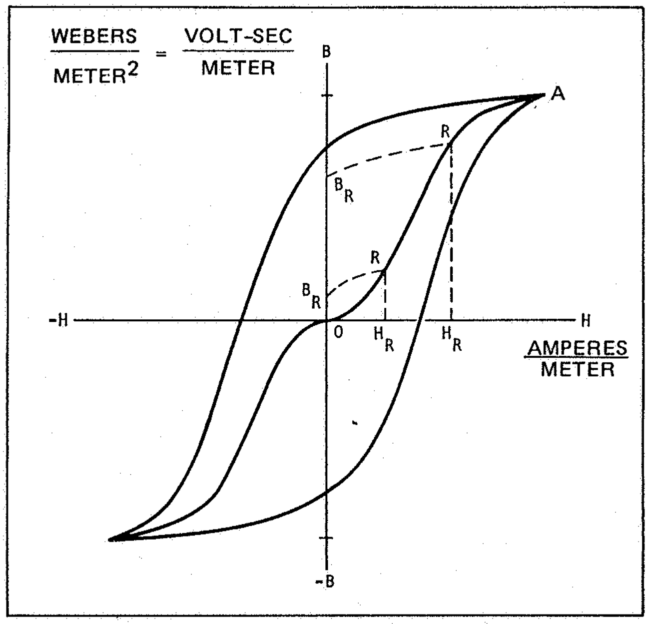


Figure 5. A Typical Magnetization Curve, or Hysteresis Loop

but the magnetization of the particle will follow a minor hysteresis loop, RB_R, retaining a residual, or remanent magnetization of B_R. The transfer characteristic of this process is shown graphically in Figure 6 and its inherent nonlinearity is readily apparent. High distortion in the reproduced signal results unless some corrective action is taken.

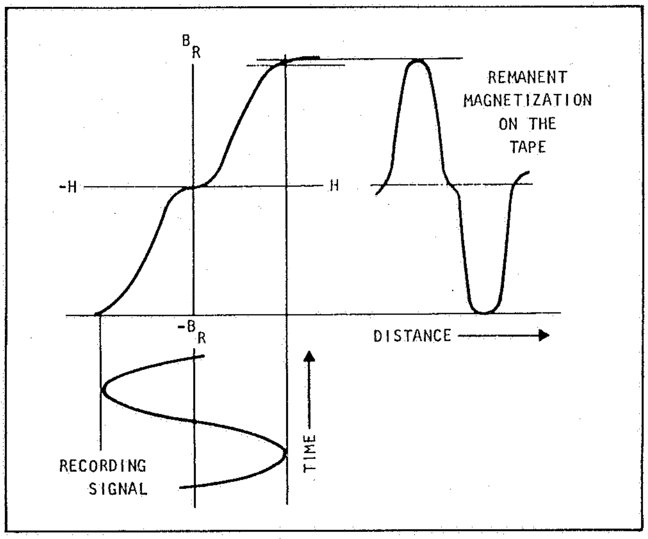


Figure 6. Head-to-Tape Transfer Characteristic with No Bias

Fortunately, there are two fairly linear segments in the transfer characteristic curve, one on each side of the origin with their center about half way to saturation. (See Figure 6). If the recording can be confined to one (or both) of these straight sections, low distortion can be realized. Similar to the manner of biasing a vacuum tube into a region of linear operation, some method of "biasing" the recording function into the linear transfer region must be used. Early recorder designers went naturally to a dc bias produced simply by adding a constant dc current to the signal and obtained operation in one or the other of the two linear ranges. With the relatively limited range thus available, dc-biased recorders give a very restricted dynamic range, but they are quite improved over zero-bias recording. If both linear sections of the curve are to be used, some means of rapidly switching from one to the other must be devised. This is exactly what a high-frequency ac bias does. There are several theories about how an ac bias performs this function, and no one of them really accounts for all aspects. One of the older and still widely accepted theories, however, is that since the bias itself is not seen at the output of the reproduce head, because of its high frequency, its switching function is not detectable and the gap between the two linear sections disappears.

Figure 7 shows graphically how a low-distortion magnetic signal is thus recorded. Some further reduction in nonlinearity is also obtained in the same way as in push-pull amplifier operation, since nonlinearities are symmetrically disposed around the origin.

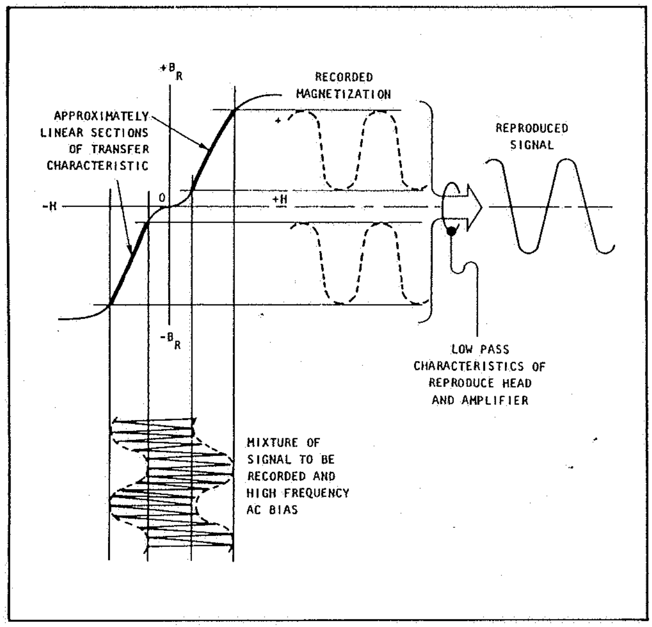


Figure 7. Graphical Representation Showing How AC Bias Alternately Transfers the Signal from One Linear Section of the Curve to the Other

Several features of ac bias operation are worth noting: (1) It should be emphasized that the bias and the signal are linearly mixed (or added) together. It is not a modulation process. (2) The proper amplitude for the bias is dependent upon the exact transfer characteristic of the tape and should be adjusted to reach from center to center of the linear regions. Too much bias will greatly reduce the high-frequency response, while inadequate bias will cause increased distortion of the lower frequencies. (3) Bias frequencies are usually not critical, but should be at least 3.5 times the highest frequency to be recorded to minimize interaction with harmonics of the signal. (4) Care must also be taken to provide a harmonically pure sinewave bias current to minimize distortion products.

In practice, bias currents from 1.0 to 20.0 milliamperes are common, and they may be from 5 to 30 times the signal current, depending upon the tape and head characteristics.

2.1.2 HIGH-FREQUENCY RESPONSE.

Several factors combine to limit the high-frequency response of tape recorders, but before these are discussed we should understand what is meant by recorded wavelength, resolution, and packing density.

If a sinewave signal is recorded, the magnetic intensity of the recorded track will vary sinusoidally. The distance along the tape required to record a complete cycle is called the recorded wavelength, or λ, and is directly proportional to tape speed and inversely proportional to signal frequency. For example, a particular recorder quotes 60 kHz response at 15-ips. There are several other ways to describe this response. Dividing 60 kHz by 15-inches shows the machine is capable of a packing density of 4,000 cycles per inch. Such a signal has a wavelength of .00025-inch which is the limit of the machine's resolution. Both packing density and resolution can be used to describe a recorder's response independent of tape speed, and thus are more definitive of a recorder's capability than just a frequency specification at a given speed.

Seven factors contribute to the high frequency limitation of tape recorders. They are (1) gap effect, (2) recording demagnetization, (3) self-demagnetization, (4) penetration losses, (5) head losses, (6) separation loss, and (7) azimuth misalignment.

1. Gap Effect. As shown in Figure 8, the reproduce head output increases with frequency up to a point and then decreases rapidly to zero. The decrease is primarily the result of gap effect and occurs as the recorded wavelength (λ) becomes shorter and shorter until it eventually equals the reproduce gap dimension itself. At this point there is no magnetic gradient spanned by the gap and thus no output voltage. This is the most serious, single restriction on a tape recorder's high frequency response. Figure 8 shows a graphical representation of the gap effect.

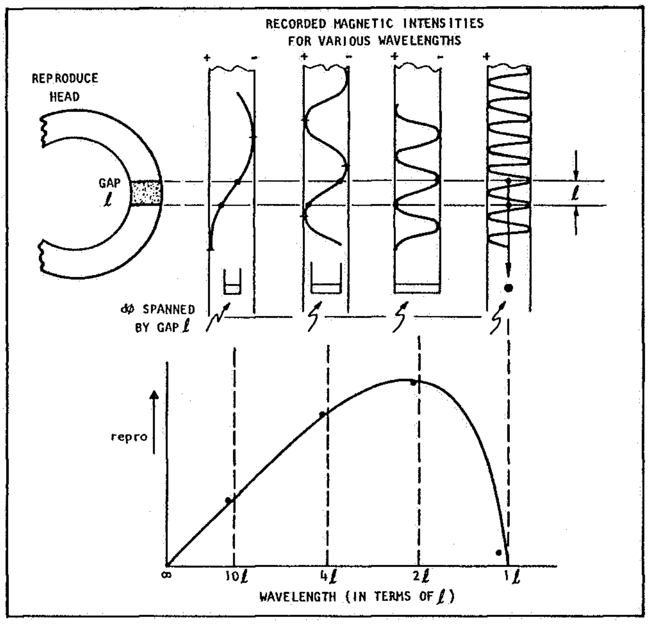


Figure 8. A Graphical Representation of Gap Effect

2. Recording Demagnetization causes a decrease in the reproduced signal level at the shorter wavelengths, and, as the name implies, it occurs in the recording process. Normally, with the longer wavelengths, the particles on the tape are being driven through large symmetrical hysteresis loops by the ac bias while in the influence of the recording field. These loops are offset by the much smaller recording signal and as the particle leaves the field the loops collapse leaving the particle magnetized in proportion to the signal. For shorter wavelengths the recording signal may vary considerably as the particle is leaving the field and a corresponding reduction in the remanent magnetization will result.

3. Self-demagnetization occurs in the magnetic medium itself when the external magnetizing force is removed and is most pronounced when magnetic poles are crowded closer and closer (shorter wavelengths). Actually, self-demagnetization is probably the least important of the high frequency limitations.

4. Penetration losses are wavelength-dependent and cause another reduction in the reproduced signal level. The full depth (or thickness) of the magnetic coating on the tape becomes magnetized at long wavelengths, but as the wavelength decreases the depth of magnetization is reduced and, at very short wavelengths, only the surface layer of particles are effectively magnetized. Thus, the shorter wavelengths influence fewer particles, there is less intensity in the recorded magnetic pattern, and the reproduced output falls off.

5. Head losses. Unlike the limitations discussed above, head losses are not wavelength dependent, but like any ac-driven ferromagnetic material, are related strictly to frequency. Both core and winding losses act to reduce the effective recording current at the high signal frequencies. Hysteresis and eddy-current losses in the core material and the distributed capacity of the windings are the major contributors and, of course, they increase with frequency.

6. Separation Loss. This effect is seen in the reproduced signal as very short and random reductions (or dropouts) in signal level. Actually, dropouts are not caused by the recorder, but result from imperfect tape-to-head contact. A detailed discussion of dropouts and head separation will be found in paragraph 6.2. Modern tape technology has reduced dropout problems by several orders of magnitude but they have not been eliminated. It is interesting to note that in audio recording, dropouts cause very little problem because the human ear tends to integrate short amplitude variations and with this smoothing process they are not discernible.

7. Azimuth misalignment. Short wavelength losses occur when the reproduce head gap is not precisely parallel to the record head gap. These are defined by the equation:

$$\text{Loss (db)} = 20 \log \frac{\sin[\pi W (\tan A)/\lambda]}{\pi W \tan A/\lambda}$$

W = track width

Where: A = angle of misalignment (radians)

λ = wavelength .

For example, with a track width of 37 mils and a wavelength of .25 mil, a 3 db loss occurs for a 1/6 degree (.003 rad) misalignment. Obviously, proper head alignment is important in reducing azimuth losses, however, there can be other contributors such as oversized or worn tape guides, subnormal tape widths, improper capstan pressure roller alignment, etc. On extremely wideband recorders azimuth adjustment screws are built into the reproduce head stack mounting base. Optimum reproduce head azimuth can be obtained by "tweeking" this adjustment to maximize the reproduced high frequency signal. It is interesting to note that all heads in a reproduce head stack may not be optimum for a given azimuth setting.

2.1.3 OTHER CHARACTERISTICS.

In the discussion of bias it was shown that the linear range of the transfer characteristic gradually became nonlinear as magnetization approached saturation. This gives the recording process what is aptly described as "graceful" limiting, or in other words, increasing the recording level above normal will gradually increase distortion before hard limiting, caused by magnetic saturation, occurs. To define the maximum signal level which can be recorded, it is thus necessary to state the maximum distortion which can be tolerated. In practice, the specified maximum signal level is usually tied to a 1% total harmonic distortion (THD) specification.

Dynamic range or signal-to-noise ratio is quoted in db and is the ratio of the maximum signal (for a given THD) to the minimum signal which can be recorded; the minimum signal being determined by the noise level of the entire system over the bandwidth of interest.

Before we leave the direct record process, the problems associated with the use of audio recorders for instrumentation work must be discussed. Probably every reader is familiar with the large variety of audio recorders that are available today. Most of them do an excellent job recording voice and music, but they must not be confused with instrumentation recorders. They are actually a very specialized case of the direct record process. Comparing the specifications of audio and instrumentation recorders will readily show some differences. For example, audio recorders quote response down to 40 or 50 Hz and signal-to-noise of 50 to 60 db, while instrumentation recorders stop at 50 Hz and have S/N ratios of 24 to 38 db. Only when the purposes of the two types of recorders are examined can these differences be reconciled. Audio machines are sold to record voice and music and are designed to take advantage of the rather peculiar spectral-energy characteristics of this kind of signal. Years of study, primarily in the telephone business, have shown that the energy content of such signals is not distributed uniformly over the audible frequency range, but is heavily concentrated in the mid-audio band with relatively little energy at the high or low frequency ends. As a result, each end of the band requires very little dynamic range. The audio machine's record amplifier boosts, or pre-emphasizes, these band-edge signals as they are put on the tape. When played back, the audio reproduce amplifier operates with reduced gain at the band-edges to equalize the signal and restore fidelity. This factor also improves the overall noise level of the audio recorder because it is at the band-edges that the system noise level is highest. With reduced gain in these regions the cumulative noise within the passband is greatly reduced. This fancy footwork has gained the audio recorder a lower frequency response and a lower noise level in the reproduced signal, at the cost of less dynamic range (or earlier saturation) at each end of the audible spectrum, i.e., at 50 Hz or 14,000 Hz an audio recorder may saturate with a 12 to 15 db signal, yet at 400 Hz where S/N is measured, the machine may handle a 55 db signal. This type of pre-emphasis and post-equalization has been widely accepted in audio recorders, both for home and professional use, and standard audio equalization curves have been adopted by the National Association of Broadcasters (NAB). They are similar to the well-known RIAA equalization used in the record making industry.

Instrumentation recorders cannot favor any portion of their recorded bandwidth because of the nature of the signals they must accommodate. Their low frequency response is quoted at 50 cps so that the added noise contribution below that point can be eliminated. Of course the added noise from the higher frequency response does add to the cumulative noise and reduces the S/N figure. Also, in striving for the higher frequency response, much narrower gaps are used in the reproduce heads with a corresponding reduction in signal power. The definition of maximum record level also works against the instrumentation machine, i.e., that level which produces 1% THD, while for audio recorders it is that level which produces 3% THD.

As you can see, there are many differences between audio recorders and instrumentation recorders. Some are obvious, some are very subtle. There are very few occasions when an audio machine will record instrumentation data without compromise. Be careful if you select one for your recording job.

2.1.4 RESPONSE STANDARDS FOR THE DIRECT RECORD PROCESS.

As a result of the need to insure compatibility when recorded data was to be exchanged between machines at different locations or of different origin some form of standardization was required. Table A-1 of Appendix A is reproduced from IRIG 106-73 and shows the standards established for four groups of direct record parameters. It should be noted that the IRIG Standards, first established in the early 1950's, are applicable only to 1/2 and 1-inch tape systems, while technological advances have enabled manufacturers to offer 4, 7, and 8 channel instrumentation recording capability on 1/4-inch tape. The lack of IRIG standards for 1/4-inch tape has not prevented the incorporation of the applicable high performance specifications to the newer recorders. There are many industrial, medical, government, and other users who do not require the interchange standards of IRIG, and who should be aware of the price-performance package these 1/4-inch recorders can provide.

2.2 FM RECORD/REPRODUCE.

Following World War II, the limitations of the direct record process severely restricted the use of tape recorders for general instrumentation work. By 1950 the growing aero-missile business and the several military test ranges had to record an increasing amount of dc and very low frequency test data. To serve in these areas, magnetic recording had to somehow provide dc response, good dc linearity and better signal-to-noise ratios.

The recording industry filled this need with the development of FM recording. The technique was widely accepted and the majority of recorders in use in the 1950's were equipped for FM operation. Still in wide use today, the first FM scheme used center frequencies and deviations adapted to 80 kHz to 100 kHz recorders and put a single carrier on each track, recorded to saturation without bias.

Data recording using a frequency modulated carrier is accomplished by deviating the carrier frequency in response to the amplitude of a data signal and recording it. A dc signal of one polarity increases the carrier frequency and the opposite polarity decreases it. An ac signal alternately increases and decreases the carrier above and below its center frequency at a rate equal to the data signal frequency. In the reproduce process, the carrier's amplitude instability is essentially wiped out by limiting and the data signal is reconstructed by detecting zero crossings. Residual carrier signal and out of band noise are removed by a low pass filter. BUT, FM recording has a problem of its own. It is extremely sensitive to tape speed fluctuations (flutter) since in either the record or reproduce mode, tape speed variations produce unwanted modulation of the carrier (or noise).

The increased noise level in the reproduced signal and corresponding reduction in dynamic range is the first order effect of flutter. A second order effect is the actual time base variation of the data signal, much the same as the direct recording process.

A detailed technical description of FM theory can be found in text books but a brief discussion of a few of the more pertinent factors will be made to assist the layman in a cursory understanding of the FM recording process. First, a few definitions:

f_c = carrier center frequency

Δf = max carrier deviation from f_c

f' = data signal frequency

f' max = highest data signal frequency

$\dfrac{\Delta f}{f'\,\text{max}}$ deviation ratio, or modulation index

$100\,\dfrac{\Delta f}{f_c}$ = percentage deviation .

Deviation ratio is one of the most important factors in any FM process. Basically, the higher the deviation ratio, the more immunity the system will have to noise. In FM recording, however, there are practical limits to deviation ratio since Δf is restricted by recorder bandwidth limitations and f' max must be kept high to accommodate the data signals. Common deviation ratios in use today range from 5 in the telemetry FM subcarriers to 0.675 in wideband FM recording. FM broadcasting, which enjoys an excellent noise immunity, uses a deviation ratio of 5 (Δf = 75 kHz, f'max = 15 kHz).

The percentage deviation, 100 $\Delta f/f_c$, is another factor in FM recording. When recording low percentage deviation systems, such as the FM telemetry subcarriers (7.5 percent and 15 percent), the effect of flutter is essentially multiplied with a corresponding increase in noise. For instance, if a 7.5 percent frequency deviation corresponds to a 100 percent input signal, a 1 percent deviation caused by flutter will appear as 100/7.5 = 13.3 percent noise signal. The same flutter imposed on a 40 percent deviation system will cause only 100/40 = 2.5 percent noise signal. The higher percentage deviation systems are thus less influenced by tape speed variations but circuit design limitations make 70 to 75 percent a practical limit.

A well-designed FM carrier recording system will give reasonably good amplitude accuracy, dc response, good dc linearity and low distortion. The price paid for this improvement over direct record performance is greatly reduced frequency response for a given tape speed, added complexity and cost in the record/reproduce electronics and a much greater need for constant tape speed (low flutter).

There are many uses for FM recording. The obvious advantages, of course, are the dc response and stability. It also is a very handy tool for time expansion and compression techniques. As an example, 5 kHz data recorded at 15-ips on a 27 kHz carrier can be reproduced at 15/32-ips with the data frequency spectrum reduced by a factor of 32. Combinations of changing tape speeds and re-recording can provide time base change and frequency shift factors to well over 200. Data reduction, spectrum analysis, hard copy output, and other laboratory chores can be simplified with such expansion and compression techniques.

2.2.1 FM RECORDING "STANDARDS".

As long as recorder response was limited to about 100 kHz at 60-ips, there were fairly well defined standards for FM recording. Tape speeds 1-7/8-ips to 60-ips were assigned FM carrier frequencies from 1688 Hz to 54 kHz, all harmonically related; i.e., double the tape speed and double the FM carrier frequency. Percentage deviation was established as ±40 percent and a deviation ratio of approximately 2 was selected. The major recorder manufacturers adhered to the standards and FM recording proceeded in an orderly fashion.

From 1958 to 1965, however, tape recorder response moved up by an order of magnitude and many extensions and modifications to the old standards came into being. By 1965 there was considerable confusion in the industry and among the users regarding FM recording. Such terms as wideband FM, single carrier FM, standard response FM, extended response FM, and even double-extended response FM were used to describe the many new kinds of FM recording, but truly authoritative definitions were lacking. Finally, in 1965, an updated version of the IRIG document, "Telemetry Standards" (IRIG document no. 106-65) was published and has since been revised several times, the latest being 106-73. Table A-2 of Appendix A is reproduced from the IRIG publication and shows the tape speeds, center frequencies, etc., which are recognized as standards for 1/2 and 1-inch instrumentation tape recorders.

2.2.2 FM RECORDING SYSTEMS.

"Single carrier FM recording" is the name now used to describe the original FM technique which used saturation recording. First called "wideband FM" to distinguish it from telemetry subcarrier recording, it has relinquished this name to the new schemes which use fractional deviation ratios and are truly wideband.

The various parameters of single carrier FM recording are shown in Appendix A, Table A-2. The majority of the systems in use today still record the carrier to saturation on the tape without bias using FM electronics provided by the recorder manufacturer. In this manner, the maximum possible voltage is obtained from the reproduce head. Direct recording (with ac bias) may also be used with voltage controlled oscillators and discriminators external to the recorder.

Carrier frequencies are proportional to tape speed and have been selected near the middle of the recorder's response to keep distortion products above the passband of the head/amplifier combination. FM record amplifiers can usually be "tuned" to any of the standard carrier frequencies by selection of the proper plug-in or switchable tuning unit. Similarly, the FM reproduce amplifier is set for a specific carrier by selection of the proper frequency determining element and low pass filter.

Single carrier FM recording uses ±40 percent deviation with a deviation ratio of approximately two. Performance will usually equal or exceed the following:

Frequency response:	±0.5 to 1.0 db over the specified band.
RMS Signal-to-Noise ratio:	40 to 54 db if full deviation is used and flutter specification is 0.25 to 0.7 percent peak-to-peak.
DC drift:	less than 1 percent of full deviation over 24-hour period.
DC linearity:	Within ±1.0 percent of a zero based straight line.

If electronic flutter compensation is used, the first-order effects of flutter or flutter induced noise can be reduced to a point where other noise contributors set the noise level. At best, a signal-to-noise ratio of 50 db to 56 db may be obtained at tape speeds of 60 or 120-ips. Techniques of flutter compensation are discussed in chapter 5, Electronics.

Rotary head video recorders which appeared about 1958 also use a type of FM recording. Primarily designed for TV broadcast use, instrumentation versions of these machines can now provide outstanding performance. The cost of such a machine will certainly restrict its usage, but the fact that such performance can be provided in a production machine is an outstanding tribute to its developers.

There are two other techniques of FM recording which put multiple subcarriers on a single track. The direct recording process is used to minimize distortion and avoid crosstalk between carriers. Basically these schemes provide a means of frequency-division multiplexing of many low frequency data signals on a single tape track.

The first and oldest scheme uses the FM/FM telemetry subcarrier oscillators. Their availability and standardization long ago made their use a natural for FM subcarrier recording. A listing of their parameters is shown in Appendix A, Table A-3. Based upon a constant percentage deviation (7-1/2 percent or 15 percent), these units provide increased bandwidth with each higher center frequency. As discussed earlier, their low percentage deviation makes them highly susceptible to flutter-induced noise. Electronic flutter compensation must be used if data amplitude accuracy is important. Unlike the single carrier FM system, however, flutter compensation for multiple subcarrier recording is complicated by the characteristics of the bandpass filters, which are used to separate the subcarriers in the reproduce process. Space has been allowed in the IRIG subcarrier frequency assignments for a 17 kHz reference tone to be recorded between channels 13 and 14. Usually this reference frequency is used for tape speed compensation of the tape drive mechanism. A 100 kHz or 200 kHz reference tone is also often recorded for use by the electronic flutter compensation equipment.

The constant percentage deviation, or proportional bandwidth system fell short in supplying the need for a large number of channels having relatively high frequency response. To fill this requirement several telemetry ground equipment manufacturers provided "constant bandwidth" subcarrier systems. Deviation ratios of from 1 to 5 can be used, however, 2 is most common. Percentage deviation varies with the subcarrier frequency. A typical system might consist of a baseband of subcarriers, perhaps 5 in number. Their center frequencies and deviations might be 24 ±2 kHz, 32 ±2 kHz, 40 ±2 kHz, 48 ±2 kHz, and 56 ±2 kHz. If additional channels are required another baseband of 5 subcarriers is generated and translated in frequency to be recorded at 64 kHz ±2 kHz, 72 kHz ±2 kHz, etc. Several basebands of subcarriers can be recorded in this manner if appropriate translation frequencies are used for each. Appendix A, Table A-4 lists the standard FM constant-bandwidth FM subcarrier channels. The letters A, B and C identify the channels for use with maximum subcarrier deviations of ±2 kHz, ±4 kHz and ±8 kHz, along with maximum frequency responses of 2,4, and 8 kHz, respectively. The channels shall be used within the limits of maximum subcarrier deviation.

TAPE RECORDER HEADS

Key to the success of any recorder's performance are its heads. There are record heads, reproduce heads and erase heads. There are rare cases such as some FM carrier recorders where a single head is used for both the record and reproduce function but the great majority of instrumentation recorders use separate record and reproduce heads.

Tape recorder heads are electromagnetic transducers. A record head converts an electrical signal to a magnetic signal suitable to impose on the tape, and the reproduce head converts the magnetic signal of the tape into an electrical signal. Erase heads are a sort of specialized record head designed to saturate the tape at a specific frequency, however, they are seldom used on instrumentation recorders. When tapes must be erased, bulk erasure is most commonly used because it provides a more thorough erasing job and is less likely to be done accidentally.

The most carefully guarded proprietary secrets in the recording industry are those concerned with head manufacture and assembly. Many aspects of the assembly of high resolution record and reproduce heads are closer to being an art than a science. Successful head production is more often related to the experience and know-how of key individuals, rather than established production techniques.

The basic construction of both record and reproduce heads is similar, consisting of a magnetic core on which is wound a number of turns of wire (see Figure 9). The core consists of two "C" shaped half sections which are made from a number of bonded laminations of thin, high permeability, ferromagnetic material. The surfaces of the half sections which interface with each other are lapped and polished very carefully and the gap material is deposited on one. The two cores and their windings are then joined together to form a head.

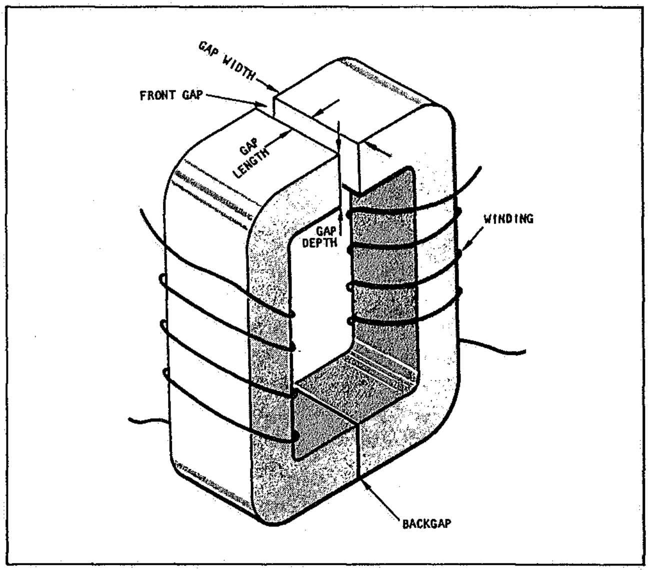


Figure 9. Head Core Showing Dimension Definitions

One head is used for each track of the tape. In multi-track operation, several heads must be assembled together with intertrack shields to form a head stack. Extreme precision is necessary in aligning the heads in a head stack since the gaps of all heads must fall within a 100 micro-inch band. After alignment, the heads are potted. The head stack is finished by contouring and lapping for optimum head-to-tape contact and then it is mounted on a precision machined mounting base by which it is secured to the tape transport. The complete head assembly thus includes a base with a mounting surface whose plane is perpendicular to the gap line at the contact surface of the head stack. It is because of the precision mounting base that head stacks may be removed for cleaning and new head stacks may be installed without factory adjustment while maintaining minimum losses due to azimuth misalignment (see paragraph 2.1.2).

3.1 RECORD HEADS.

It was explained earlier that the record process takes place at the trailing edge of the record head gap. Because of this, the record head gap length has little effect on a machine's frequency response. Most machines use a record gap length of 0.2 to 0.5 mil. The accuracy of the gap edge, however, is very important to the recorder's high frequency capability and extreme care is taken to get a sharp, well-defined gap edge.

The ideal record head/record amplifier combination will place an equal amplitude flux pattern on the tape for a given signal level, throughout the recorder's frequency range. This would truly be a "constant flux" recording. Actually, performance closely approximating this ideal condition is obtained in modern recorders, through the use of recording pre-emphasis. Both head losses and to some extent the recording demagnetization losses are made up for by the use of a high frequency "boost" characteristic in the record amplifier. Additional pre-emphasis is not used, however, since the constant flux condition is optimum for best dynamic range and minimum distortion products.

3.2 REPRODUCE HEADS.

The high-frequency response of a tape recorder is determined by the gap length and the quality of its reproduce heads. For a machine to reproduce a 2 megahertz signal at 60-ips, it must "see" recorded wavelengths on the tape as short as 30 microinches, and this requires a reproduce head gap length of approximately 10 microinches.

In addition, the gap must be sharply defined and have adequate depth to withstand the abrasive effect of the tape. The gap material and the core material must have similar wear characteristics for the gap to maintain its definition. To produce several such heads in a single headstack, in production quantities, is one of the greatest industrial achievements in the United States today. The price of such a high resolution headstack may run several thousand dollars.

The push for shorter and shorter gap lengths has one disadvantage. Unfortunately, as the gap length decreases, the output voltage from the head winding also decreases, thus lowering the signal-to-noise ratio of the recorder. It is interesting to note that one of the first symptoms of excessive head wear is increased head output at lower signal frequencies. This results with the lengthening of the gap. Even with such adverse conditions, however, present day recorders obtain 38 db or better signal-to-noise ratios while realizing packing densities of 30,000 to 33,000 cycles per inch.

3.3 HEAD CARE AND HEAD LIFE.

The care and the life of tape recorder heads are completely interdependent. Factors which can affect the life of the head during normal use include the following:

1. Cleanliness of the tape, the transport and the environment in which the equipment is operated.
2. Maintenance procedures which involve the checking of tape tension, tracking, etc.
3. The abrasiveness of the tape being used.
4. Solvents used for cleaning the heads.

Cleanliness in and around the head area is of utmost importance in all instrumentation machines. Not only can the dirt particles become a serious threat to the data "take" in terms of spacing loss, but they can also become minute scrapers, gougers, and cutters to the head and tape surfaces when dragged between them. High tape-to-head pressures are necessary to keep the spacing loss low, and such pressures not only increase the abrasive effects of the tape, but any piece of dirt is crushed that much harder into the head or tape material.

Maintenance procedures involving nearly all aspects of the mechanical part of the recorder will affect the head area in one way or another. Tape tensions must be kept as specified to ensure the optimum compromise between wear and performance. Care must be taken not to touch the heads with any metallic or hard object for fear of scratching, gouging, or magnetizing the heads.

The recording/reproducing of shorter and shorter wavelengths demands intimate contact between the oxide particles and the head gap to eliminate spacing losses. Higher tape tensions and more abrasive tape surfaces have resulted, and both tend to increase head wear. Gamma ferric oxide particles are very sharp and hard and resemble extremely fine sandpaper particles. The tape binders used on wideband tapes are also smoother and harder and form a firm base for each scratching particle. If high packing densities are not necessary, do not use premium tapes.

Clean heads are necessary if good recording is to be done. However, it is not safe to use just any solvent that appears to dissolve the residue left by the tape. The material used to hold the head cores in the head assembly is in some cases softened by such solvents as toluene, methyl ethyl ketone or xylene. If one is in doubt about the head construction, use only alcohol, naptha, freon TF, gasoline or even jet fuel!! Freon TF is probably the best all-around cleaner and is now available in an aerosol can for convenient storage and use. Most head cleaners will also dissolve lubricating greases and tape binders and should be used carefully especially around bearings and the tape. A cotton tipped applicator makes a good disposable cleaning tool for the majority of cleaning requirements.

Clean all transport parts that come in contact with the tape. Oxide buildup can cause degradation of high-frequency response, distorted record and playback, and tape and head damage. Clean tape heads with cotton tipped applicators dampened in head cleaner by rotating applicator against head surface and noting the discoloration of cotton. Use as many applicators as required to avoid wiping head surfaces with dirty applicators. When applicator comes away clean, head surface is clean. Also use applicators to clean tape guides, rollers, capstan, and pinchroller. Take particular care to clean undercut edges of guides and roller grooves. Accumulation of wear products in corners of guides or roller grooves will damage the tape.

Magnetized heads produce unpredictable results in the reproduced data. Under no circumstance should continuity of a head be checked with an ohmmeter. High second harmonic distortion results from a magnetized record head; the demagnetizing effects of the ac bias used in the direct record process, however, reduce the chance that record heads will be magnetized unless subjected to large unidirectional current surges (such as a continuity check) or close-proximity to high-intensity magnetic fields. It is unwise, therefore, to remove record electronics cards from the recorder while in the Record mode. The last current surge as one removes an amplifier may serve to magnetize the record head.

Magnetization of the reproduce head is more prevalent and affects its performance in an unpredictable fashion, though generally increased noise levels result. Demagnetization of recorder heads is accomplished by using any of the commercially available head degaussers. The recorder should always be turned off when degaussing heads and on some machines removal of the head assembly simplifies the job and ensures more complete degaussing. Proper procedures can usually be found in the recorder's instruction manual. Be sure to understand the complexity of head removal before removing the head assembly, though, as head assembly removal and replacement always requires extreme care and attention to detail.

TAPE TRANSPORT MECHANISMS

TAPE TRANSPORT MECHANISMS

The sole purpose of a tape transport is to move the tape by the heads at a constant speed and to provide the various winding modes of operation required for tape handling, without straining, distorting or wearing of the tape. To accomplish this, a transport must guide the tape past the heads with extreme precision and maintain the proper tension within the head area to obtain adequate tape-to-head contact. Spooling or reeling of the tape must be done smoothly so that a minimum of perturbations are reflected into the head area. Takeup torque must be controlled so that a good tape pack results on the takeup reel. It is also the job of the transport to move the tape from one reel to the other quickly in the fast forward or rewind mode. Even with fast speeds, the tape must be handled gently and accurately so that a good tape pack is maintained on each reel. In going from a fast mode to a stop (or vice versa) precise control of the tape must be maintained so that undue slack or stress is not incurred by the tape. Most of these functions are provided in modern instrumentation tape recorders but improvements in the area of uniform tape motion are constantly being sought.

The earliest instrumentation recorders were an outgrowth of the best audio recorders of the time. They used the open-loop transport design (see Figure 10) where the tape in the head area has only one end controlled by the capstan; the other end being tensioned directly by a reeling function. As instrumentation demands increased, audio machines were refined and specialized electronics were built with the open-loop transport predominating until the mid-1950's. It was basically a sound design, both simple and reliable, however, its flutter performance left something to be desired. There were two inherent sources of unwanted tape speed variations in the head area. One came from the perturbations caused by the supply reel, its drive motor or braking mechanism, and the other resulted from erratic vibrations in the tape because of the long unsupported tape length in the head area. Vibrations were also induced by friction between the tape and the heads or fixed guides.

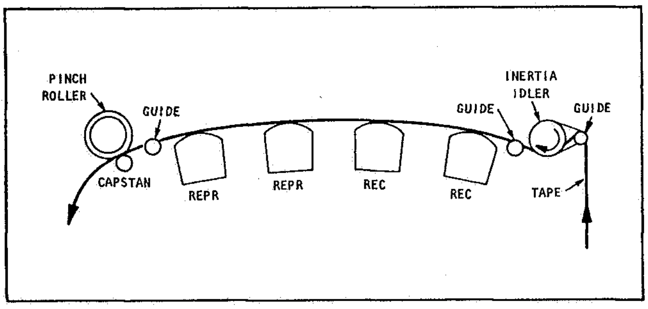


Figure 10. Open-Loop Drive

The closed-loop transport design shown in Figure 11 would seem to solve both these problems. The unsupported tape length is halved and, if both ends of the tape in the head area are under positive control of the capstan, the reeling function perturbations would be eliminated. Actually these characteristics are only partly achieved.

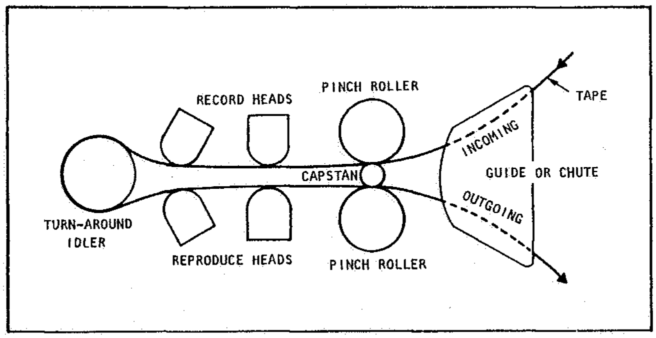


Figure 11. Closed-Loop Drive

If there were no slippage or creepage between the tape and the capstan at either point of contact, then any initial tension in the loop would be maintained. But the only elements which can apply tension to the tape are outside the loop; i.e., the reeling functions. Thus, there has to be some creep between the tape and the capstan for the reeling functions to maintain tension within the loop. So, even in the closed loop transport design, motional perturbations in the reeling functions will still cause uneven tension variations in the head area and corresponding tape speed variations, but the effects are greatly reduced when compared to the old open loop designs.

By 1958, nearly all manufacturers were using closed loop transports, but still striving for improved performance. About this time, one manufacturer developed a new capstan drive design which provides a differential action. It is basically a capstan with two discrete diameters, (only a few thousandths of an inch difference). As shown in Figure 12 special contoured pinch rollers are used and tape entering the head area is forced against the smaller capstan diameter while tape leaving the head area is forced against the larger capstan diameter. Thus tension is generated within the loop because of the speed differential between the tape entering and the tape leaving the loop. In this design, less tape tensioning is necessary from the reeling functions and more isolation is obtained in the head area from reeling perturbations. However, the drive is not suitable for bi-directional operation.

There is yet another type of transport configuration which is now widely used. This is the two capstan transport shown in Figure 13 and called dual-capstan or differential capstan. Some designs turn both capstans at the same peripheral speed and rely on the reeling functions to establish the tape tension in the head area; much the same

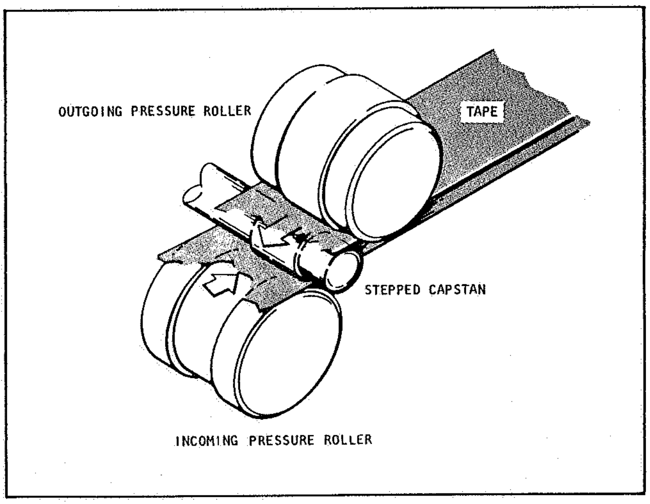


Figure 12. Two-Diameter Capstan

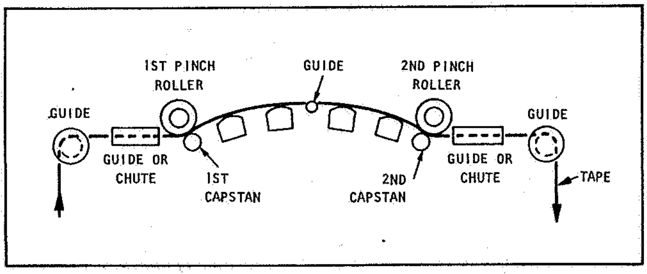


Figure 13. Dual-Capstan Closed-Loop Drive

as the conventional-closed-loop transport. However, most two-capstan machines turn the capstans at slightly different peripheral speeds and establish the tape tension in the head area with this differential action. Less tension, external to the head area is required and considerable isolation from reeling function perturbations is thus obtained.

In the mid 1960's the open-loop transport reappeared in a refined form which competes quite well with the more sophisticated closed-loop designs. A major effort in one manufacturer's design shown in Figure 14 was devoted to the use of swinging damper arms with a high inertia high torque capstan. The significant reduction in the length of unsupported tape allowed for a substantial improvement in high frequency flutter.

All in all, the new open-loop design retains all the simplicity of the old, yet provides greatly improved performance at considerably less cost than most closed-loop machines.

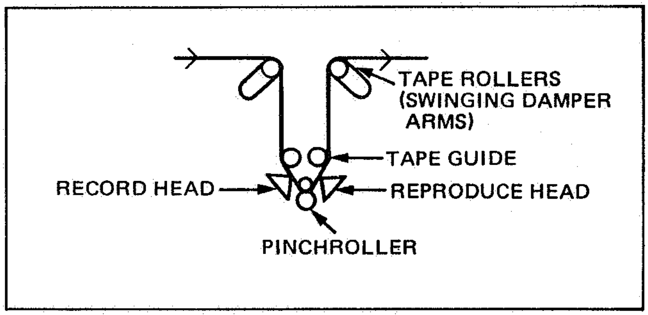


Figure 14. Refined Open-Loop Drive

Another feature which appeared in transport designs is the elimination of the pinch rollers. These drive systems use a capstan with high surface friction and large tape-wrap angles. When used with the dual (differential) capstan drive, reasonable isolation is obtained from reeling perturbations. One design, however, is similar to the closed-loop transport, with the high surface friction capstan replacing the turn-around idler. In this machine, tape tension in the head area and isolation from reeling perturbations is provided by vacuum controlled tape chutes before and after the record and reproduce heads. Flutter and skew performance of this machine are said to be excellent.

With the elimination of the pinch roller, one more source of tape speed irregularity and tape guiding is removed. Pinch rollers with surface deformations, slick or sticky spots, or noisy bearings can be large contributors to a machine's flutter and dynamic skew.

4.1 TAPE REELING MECHANISMS.

Early tape transports provided the necessary reeling functions by simply putting a torque motor on both the supply and takeup reel shafts. Both ac and dc torque motors have been used, and they are designed to give an essentially constant torque over a wide range of speeds without over-heating at extremely slow speeds. Holdback tension on the supply reel side is obtained in several ways; i.e., a simple mechanical drag brake, or reverse electrical torque. The tension created this way will vary from full reel to empty reel however, because of the changing radius of the tape pack. Minimum tension is provided with a full reel and maximum tension with one almost empty. Both schemes also contribute short term tension variations because of irregular braking action or cogging pulsations in the torque motor. When such tension variations are transmitted to the head area, the transports flutter performance will suffer. Much design effort has been spent to eliminate these perturbations with varying degrees of success. Most schemes use some form of tape pack sensor, to determine the amount of tape on the reel. One method uses a rolling idler on a lever arm which rides on the tape pack. As the arm moves, a linkage controls the braking action of a mechanical drag brake. A similar version uses the same lever arm to position a potentiometer which controls the tensioning voltage applied to the torque motor. Other sensing devices include the use of photoelectric cells, a lightly loaded spring arm which tracks the exit point of the tape from the reel, etc. The necessity for such sophisticated controls is, of course, dependent on the transport design and only those machines that are most vulnerable to reeling perturbations must use these techniques.

There is one highly desirable feature which the author feels should be included in every tape recorder reeling mechanism. This is a fail-safe function in the form of a band or disc brake mounted on the reel shafts to bring the tape to a safe controlled stop in the event of a power failure. Some older machines do not have such a feature, and in the fast forward or rewind mode, a power failure can put several hundred feet of irreplaceable data into a horrible pile of creased, stretched and mangled tape.

The packaging of tape recorders is to some extent dictated by their ultimate use. The applications have imposed severe limits on the size of the recorder but the user has not been willing to reduce the recording time. As a result, a variety of reel configurations have been developed; often at the expense of simplicity of the recorder, ease of threading and loading/unloading of the tape.

The side-by-side reel transport, i.e., one on which both reels turn in the same plane, is the most convenient and conventional way to move tape past the heads. However, space recorders and some other data acquisition recorders, where volume is at a premium, use a concentric reel transport, one on which the reels are stacked one on top of the other. Concentric reel machines require a complex mechanical assembly at the reel hub, both in respect to the reel drive and tape-reel loading and unloading mechanisms. They also have a complex tape path and unless great care is taken in their design, they will have rather poor skew characteristics.

4.1.1 NATIONAL ASSOCIATION OF BROADCASTERS (NAB).

The term NAB, often used with reference to tape reels and equalization, is derived from the National Association of Broadcasters. This organization is composed of members involved in and concerned with all phases of commercial radio broadcasting – AM, FM, and TV. NARTB is the older term for the same organization which stands for the National Association of Radio and Television Broadcasters.

4.2 SPEED CONTROL SYSTEMS.

Since the capstan is supposed to control the tape speed, its driving power in early tape recorders was chosen for constant speed. The most popular choice was the hysteresis-synchronous motor. Such a motor runs phase-locked to the ac power frequency and its long term speed stability is thus as good as the power line frequency stability if operating with a constant load. With a varying load its phase relation with its supply frequency will vary but it will not "slip a pole" unless it is overloaded. The pole construction of these motors also causes a small periodic variation, or "cogging" in their torque output. Considerable smoothing must be supplied by a fly-wheel and sometimes the elasticity of a drive belt. Such a system is best described as a high-inertia low-torque drive.

Dependency on power line frequency for speed stability in many applications is a strong disadvantage. Even in laboratory use, with a metropolitan power source, some instability can be expected. Such a power source will show extremely good long term stability but short term variations as high as ±0.25% are not uncommon. These factors long ago led to the development of precision 60-Hz power supplies consisting of very stable 60-Hz frequency sources (tuning forks or counted-down crystal oscillators) and power amplifiers capable of 50 to 150 watts. Capstans powered by this means are independent of power line frequency fluctuations but suffer disadvantages in size, weight and power consumption.

There have been several quite satisfactory constant speed drive techniques using dc motors. One of the earlier methods placed an ac tachometer generator on the capstan motor shaft. Its output was rectified and compared with a dc reference voltage. The output of the comparator was then used to control the speed of the capstan motor.

Another technique drives a tone generator with the capstan motor and its output goes to a series of frequency dividers. A speed selector switch then selects the appropriate divider output for phase comparison with a highly stable reference frequency. The output of the phase comparator is then used to control the field current of the shunt-wound dc capstan motor. When both signals are locked in phase, the speed of the motor is constant. This control method, in addition to being independent of line frequency, has several advantages over the ac drive. One relates to the ease of changing tape speeds. Simply switching one more divide-by-two circuit into the divider circuit will double the motor speed. Another advantage is the reduced size, weight and power since a high-power, low-efficiency amplifier is not required.

Early dc powered capstans were also relatively high inertia systems, but with somewhat more torque than the ac drives. There is increasing usage of dc permanent magnet motor which uses a printed circuit rotor with many poles. This device has made possible a low-inertia high-torque drive system, which several manufacturers have incorporated in their recorders.

Standard tape speeds of 120, 60, 30, 15, 7-1/2, 3-3/4, 1-7/8, 15/16, and 15/32 inches per second are available and most instrumentation recorders provide easy selection of three to six of them. Some of the earlier recorders required drive belt changes if a speed change greater than 2-to-1 was required.

Any of the above methods of capstan drive control will give reasonably accurate tape speed in the record operation. If precise reproduction of recorded data is required, however, then servo speed control is necessary in the reproduce mode. There are several techniques used for this and they all operate from a reference signal recorded on the tape with the data signals.

If the recording machine is driven by a hysteresis-synchronous capstan motor, its precision 60-Hz supply is used as the reference signal and is recorded by modulating a 17-kHz carrier. If a dc capstan motor (other than the new low-inertia versions) powers the recording machine then the 60-Hz reference is generated from the speed-determining reference oscillator and recorded in the same manner. Thus either system can provide a reference signal which can be used by either system. Servo control of a hysteresis-synchronous reproduce machine is accomplished by recovering the reproduced 60-Hz reference signal and phase comparing it with the local precision 60-Hz reference voltage. The output of the comparator is a dc or very low frequency ac signal which controls the output of a 60-Hz voltage controlled oscillator. This output is then amplified and used to drive the capstan motor. The servo action effectively locks the recorded reference signal to the local precision reference signal and a length of tape equivalent to one cycle of the recorded reference is passed through the machine for each cycle of the local reference. Servo control of a reproduce machine with a dc capstan drive is usually accomplished by replacing the local tone generator signal with the reproduced reference signal from the tape.

Both methods are phase comparison systems and thus are basically positional servos. Pull-in range is limited by the high mass of the capstan drives, but the higher torque capability of the dc motor gives that system a small edge. Pull-in ranges from 1/2 to 3 or 4 cycles are probably the limit of their response.

The appearance of the low-inertia high-torque dc motors for use in capstan drives brought a totally different reproduce speed control into existence. The "snappy" response of these devices made it possible to eliminate practically all long and short term speed variations up to 100-Hz or more. The majority of these systems use a dual servo control system embodying a rate control function and a positional control function. For recording, there is an ac tachometer generator attached to the capstan shaft which produces several hundred cycles for each capstan rotation. Frequency variations in this tachometer signal are sensed by a discriminator and become a dc control voltage for the capstan motor. Basically a rate servo, this control is used to bring the capstan to the proper speed. The tachometer signal is also phase compared to a local reference oscillator after the proper speed is reached and phase locked operation is provided. During record, the signal from the reference oscillator is also recorded on the tape. For servo control of the tape speed in the reproduce operation, the recorded reference is used to replace the tachometer generator and essentially the same operation just described takes place.

Flutter specifications are very similar for both the high inertia and the low inertia capstan drive systems, as far as percentage flutter is concerned. There is, however, a marked difference in the spectral components of the flutter in the two systems. The high inertia system will exhibit greater amplitudes of low flutter frequencies and only the usual higher frequency flutter caused by tape scrape and vibration. The low inertia systems, when servo controlled from the tape, will practically eliminate the low frequency flutter but in being so responsive they actually add to the normal high frequency flutter by a form of spectrum spreading.

Even though both systems seem to show approximately the same total flutter percentage, there is a strong point favoring the low inertia system; i. e., the dramatic improvement in time base error. Specified TBE on some of these machines ±0.5 microsecond absolute. This means between two points, anywhere on the tape, the timing error will be no greater than ±0.5 microsecond ± the crystal reference tolerance.

4.3 TAPE MOTION IRREGULARITIES.

Ideal tape motion may be simply defined. The tape must move across the heads with an absolutely uniform, precisely known velocity. Actually, no tape transport will ever attain this ideal motion though improvements are continuously being made. Medium or long-term deviations from the desired average speed can be corrected by servo means as previously discussed. In fact, the low-inertia high-torque capstans are snappy enough to correct some of the short-term variations, but in general, all short-term variations cannot be eliminated in this manner. As a result, they must be considered among the basic characteristics of a recorder.

4.3.1 FLUTTER.

Short-term speed variations which are uniform across the tape can be caused in many ways in a tape transport mechanism. Some of these are: pulsations of the torque motors, reel eccentricities, irregularities in the tape pack or tape physical characteristics, vibrations in the tape caused by friction as it passes over fixed guides or heads, mechanical run-out of rotating parts, slight cogging of the capstan drive motor, power line voltage transients which may affect the motors, pinch rollers with surface deformations, sticky bearings, etc. The problem is further compounded by reels and reel drive assemblies which have varying velocities and a mass which is constantly changing.

Velocity variations that are uniform across the tape have been variously described as flutter and drift. Flutter denotes variations in speed which occur at frequencies above .10-Hz, and drift (or tape speed accuracy) is used for those frequencies below 0.1-Hz. As applied to instrumentation recorders, common usage has broadened the definition of the term "flutter" to include all variations 0.1-Hz to 10-kHz. Time displacement error (TDE), time base error (TBE) and jitter are terms used to describe the same tape speed variations from a different point of view. These terms are sometimes improperly used and some confusion can result in trying to describe the ability of a recorder to reproduce a signal with its original time relationships. It should be remembered that TDE, TBE or jitter figures must state the time over which they were measured and flutter must be quoted in either rms or peak-to-peak values over a specific band of frequencies.

The flutter spectrum of a well-designed machine is made up of a combination of small, discrete sinusoidal components and a more-or-less uniformly distributed noise signal. Because of the noise involved, a clear, well defined measurement of flutter is difficult. The flutter signal itself can be obtained by recording an extremely stable reference sinewave and passing the reproduced signal through an FM discriminator. The signal thus generated would be zero if the tape speed were exactly the same for reproduction as for recording. Any variations between the two speeds will deviate the frequency of the reference tone and produce an output from the discriminator. It is customary to measure flutter components to at least 10-kHz in instrumentation recorders. The flutter meter is the most common device used to make the peak-to-peak flutter measurements when verifying flutter specifications.

One common form of flutter specification is "cumulative flutter" measurement. This can be made by passing the flutter signal through a variable cutoff, low-pass filter and measuring the filter's output for increasing values of cutoff frequency.

Since the noise contribution in the flutter signal is essentially uniform the shape of the cumulative flutter curve will rise with frequency. At each point where some rotating component produces a discrete sinusoidal contribution there will be a small step function in the cumulative curve. Many manufacturers publish curves of this type but they are usually the average results of testing many transports and will not show the extremes that may be found in individual machines.

An rms measurement for flutter has long been used for audio machines but the peak-to-peak measurement is more useful for instrumentation machines. Actually, a true rms value of flutter is almost impossible to attain since the flutter signal contains a dc component, a noise component and many sinewave components. As a very rough approximation, the rms value can be assumed to be 1/6 to 1/4 of the peak-to-peak value.

There are many techniques used for measuring time base perturbations caused by flutter. Basically they all involve comparison between a precise electronic time delay and the time base represented by some length of tape. A reproduced pulse from the tape is used to initiate the electronic delay, and some period of time later, a second pulse from the tape is compared with the electronically delayed pulse for time coincidence. Time mismatch between the two pulses then represents a time base error attributable to tape speed variations. The equipment to accurately make such measurements is costly and not readily available.

4.3.2 SKEW.

The term skew is used to describe the fixed and variable time differences between the several tracks of a single headstack. It implies that the tape is moving in some manner other than longitudinal as it passes the heads, i.e., skewing or yawing. Fixed, or static, skew contributes a constant relative timing difference and dynamic skew produces a variable timing difference between tracks.

Fixed skew is usually caused by misalignment of head to tape, misalignment of individual heads in a headstack, and misguiding which will produce fixed differences in tension distribution as the tape crosses the heads. Dynamic skew is produced when there is uneven tension distribution across the tape. Such flutter producers as tape scrape and vibration will initiate dynamic skew.

Fixed skew and some forms of dynamic skew produce relative timing errors between the tracks which are proportional to the track spacing. There is some dynamic skew, however, which is caused by tape dimension irregularities and random flutter components, and the timing errors so produced are not correlated.

As with flutter, skew errors are imposed by both the recording operation and the reproducing operation. Tapes reproduced on the same machine they were recorded on will have less skew error than those reproduced on different machines.

Tape transport specifications usually show skew, or dynamic skew or total interchannel time base error (static and dynamic). Figures are given for different tape speeds and some of the modern machines can provide ±0.5 microsecond or better at 120-ips between adjacent tracks on the same headstack.

4.3.3 STRETCHING.

There is another source of timing error which will occur between odd- and even-numbered tracks due to the spacing between the two headstacks. If the physical dimensions of the tape vary due to environment or stretching, after the recording is made, a corresponding timing error will occur when it is reproduced. As an exaggerated example, suppose there is to be a 1-percent change in part of a tape's length. This represents 15 mils for a distance of 1.5 inches, and might represent many wavelengths of recorded signal. The less the spacing distance between the headstacks, the less loss of signal will be observed for the same change in tape length.

Differences in tape tension between the record and reproduce machines can also contribute to this type of timing error. NOTE: Gross timing errors will result if data is recorded on one machine and reproduced on a machine with a different track format.

4.3.4 EFFECTS OF FLUTTER.

Flutter has several harmful effects on recorded data. Perhaps best known is the noise it produces in FM carrier recordings. A constant frequency carrier will be frequency modulated by tape speed variations and when the carrier is reproduced and discriminated the expected dc output will also include the noise of the unwanted modulation. When the carrier is modulated with a data signal, then this noise is added with the data in the demodulation process. Thus flutter's first order effect is to increase the noise level of the reproduced signal with a corresponding reduction in dynamic range. For a given percentage flutter, the ability of the flutter noise to interfere with the data signal is dependent on the deviation ratio of the FM carrier system being recorded (see FM Recording Systems, paragraph 2.2.2).

In the direct record mode, flutter primarily perturbs the time base of the reproduced signal. Akin to this, but somewhat more subtle, the reproduced waveform will show broadening of its spectral components in a spectral analysis.

ELECTRONICS

The electronic circuitry of an instrumentation magnetic recorder performs two distinctly different tasks: tape speed control and data handling or signal conditioning. Each performs rather independently of the other, with an inter-dependency being realized in the quality of the reproduced data. Tape speed control systems were discussed in the previous section and the remaining electronics will be covered here. Each type of record/reproduce operation requires its own rather specialized electronics, but only the direct and single carrier FM modes are described. Flutter compensation circuitry will be briefly introduced with the FM electronics.

5.1 DIRECT RECORD/REPRODUCE.

The direct record/reproduce operation requires an amplifier-head driver, a bias oscillator, a reproduce head preamplifier, and a reproduce equalizer-amplifier. The amplifier-head driver is more commonly called a record amplifier and it provides several functions. It should present a nominally high impedance to the data signal to minimize loading of the signal source. A first approximation of its gain/frequency characteristics would suggest a constant current output for all frequencies. Unfortunately, the impedance of the record head will change quite drastically over the frequency range covered by modern wideband machines. Also, as mentioned previously, a constant flux recording (equal magnetic intensity on the tape for all frequencies) is ideal, yet head losses and recording demagnetization are a function of frequency. For these reasons it is customary for the record amplifier to provide increased output, or pre-emphasis, at the higher frequencies. This should not be confused with the exaggerated pre-emphasis used in audio machines: only the high frequency boost required to approximate a constant flux recording is used. As an example, one wideband machine provides 8 to 10 db of pre-emphasis at 1.5-MHz. Another function of the record amplifier is to add the bias signal to the data signal, while providing a buffer for the bias oscillator.

Somewhere in the recording circuitry a monitor point is often provided to allow observation of the record head current waveform. Usually the monitor level is about 10 ohms above ground and presents a very low-level signal. Considerable gain is required in the oscilloscope for proper viewing. Waveforms at this point, especially on the wideband machines may appear quite distorted, and the machine's instruction book should be consulted for details on their use. Recording levels should be set to obtain an optimum matching between the dynamic ranges of the data signal and the recorder. A well designed record amplifier will not saturate before the tape does, and it should be remembered that saturation of the tape is a somewhat gradual process with very quick recovery. The distortion that results when the tape is over-recorded can sometimes be tolerated in exchange for the slightly increased dynamic range.

A record level meter is often provided on each record amplifier but they are of little use if the data signal is not sinusoidal. Low duty cycle pulse trains can be drastically saturating the tape with little or no indication on the conventional rms meter. Peak reading meters have been offered by some manufacturers as an accessory but they are, unfortunately, not in wide use.

The bias oscillator must operate at several times (3.5 to 5.0 or more) the highest frequency the recorder can handle. A pure sinusoidal waveform is required since any distortion will be reflected by the recorded signal. A single bias oscillator is used to eliminate sync or "beating" problems.

A buffer amplifier, usually located in the record amplifier, provides the necessary bias drive for each track and at the same time eliminates the possibility of crosstalk between channels from occurring through the bias distribution wiring. Integral with this buffer amplifier, there is sometimes provided a convenient means for monitoring bias current on the record level meter.

The output of a reproduce head can be a very small signal, i.e., a very few microvolts in a wideband machine. At these levels the signal is subject to all kinds of noise pickup and ground loop problems. The output of the reproduce head is immediately applied to a preamplifier, through a carefully shielded cable of minimum length. To a large extent this preamplifier sets the system noise level and great care must be taken in its design to provide low noise operation and optimum impedance matching with the head. The ideal design will probably result with integrated circuit preamplifiers embedded in the reproduce headstack, but as of this writing this has not been attained yet in a production machine.

The next operation on the reproduced signal is accomplished by a reproduce amplifier. This is the unit which equalizes the reproduce head's output/frequency characteristic. When a voltage amplifier is used a 6-db-per-octave rolloff must be inserted from the lowest frequency to the mid-frequency peak of the head's output curve. At this point, regardless of amplifier type, an increasing amount of gain (up to 12 or 18-db-per-octave) must be added to compensate for the drooping head output characteristic and, to some extent, other high-frequency losses. A different equalizer network is required for each tape speed in order to properly match the different head output curves, and each network has two to four adjustments associated with it. Each adjustment affects a specific portion of the response curve and when properly set can provide the machine's specified response. Particularly in the wideband machines, one of the adjustments is usually associated with phase response. It is used to provide phase equalization, or in other words, to ensure that the various spectral components arrive at the output with the proper time relation. Phase equalization is especially desirable when reproducing pulse type data signals to minimize overshoot in the reproduced waveform.

Selection of the proper equalizer network for the tape speed in use varies from one type machine to another. In some, selection is automatic with speed selection; in others, switching with a front panel control is required and others require replacement of plug-in units when speeds are changed.

The last function of the reproduce amplifier is to bring the signal to a standard output voltage and impedance level and perhaps provide for switching to a meter for monitoring.

5.2 FM RECORD/REPRODUCE.

Single carrier FM recording electronics are supplied by the recorder manufacturer as plug-in units which can be interchanged with the direct record/reproduce units. An FM record amplifier contains an amplifier, an oscillator whose frequency varies with the data signal and an output amplifier used primarily as an impedance match for the record head. As indicated earlier, the signal is recorded to saturation on the tape at a constant amplitude. Each tape speed requires a different center frequency and in the record amplifier this is provided for with plug-in or electrically switchable frequency determining units. Typical oscillator circuits are multivibrators or a modified phantastron design.

An FM reproduce amplifier contains an amplifier to raise the level of the head output, a limiter, an FM demodulator, a low pass filter and an output amplifier to bring the signal to a standard output voltage and impedance level. The design of the first amplifier is not critical since the saturated signal already enjoys an excellent signal-to-noise ratio on the tape, and the center frequency is located to minimize head output variations over the frequencies used. A hard limiting operation is used to eliminate amplitude variations and provide a standardized signal to the demodulator. Several types of demodulators are used. The simplest method is nothing more than a zero crossing detector, which triggers a constant energy pulse for each crossing. A one-shot multivibrator may be used with the real challenge lying in developing the constant energy pulse. Both pulse amplitude and duration must be precisely constant since these are the basis for the accuracy of the reproduce unit. The resulting pulse train is then passed through a low-pass filter to remove noise and residual carrier components, and amplified to provide a standardized output. Another demodulation technique sometimes used consists of a phase-locked oscillator whose frequency is phase compared to the reproduced signal. Differences in the two frequencies produce an output used to drive the local oscillator to obtain a null. The driving voltage thus is a duplicate of the data signal. Again a low-pass filter is used in the output. As with the FM record amplifier, plug-in or electrically switchable elements are used to set center frequencies and filter characteristics.

The harmful effects of flutter cause serious deterioration in an FM recorded signal. If the utmost resolution is to be obtained a method of flutter compensation must be used. One of the simplest forms of compensation is provided by demodulating a reference signal which was recorded with the data (on a separate track) and thus generating the flutter signal itself. This signal is then simply subtracted from the many data channels as they are demodulated. Great care must be taken to match the phase and gain characteristics of both the reference and data demodulators. In a similar system, the flutter signal is similarly recovered from the recorded reference but is used to control the duration of the constant energy pulses being generated in the data demodulator.

Other FM recording techniques include the wideband FM, constant bandwidth FM subcarrier and the IRIG proportional bandwidth subcarriers. The equipment for using these techniques is almost totally supplied by the telemetry ground equipment manufacturers and their signals are all recorded by the direct record mode. They are not peculiar to tape recorders and will not be discussed here.

5.3 OTHER FEATURES.

5.3.1 REMOTE CONTROL.

Nearly all operating modes of magnetic recorders are controlled by relays or electronic switching. When using remote control the operating-mode is controlled by momentary contact switches, either by closing or in the case of the Stop circuit by opening appropriate circuits. Remote controls permit the activation of all transport modes from another position, with the exception of turning power on and off. Other indications of the recorder's mode of operation often presented at the remote control include a tape break indicator, a tape remaining meter, an indication of tape speed, and a capstan servo sync indicator. With today's emphasis on interface standards among electronic measuring devices the ability to interface the remote capabilities of instrumentation recorders further increases the machines flexibility.

5.3.2 BI-DIRECTIONAL RECORDING.

This capability has been made possible by the dual capstan transports and improved reel servo systems. At least one manufacturer has used this technique to greatly extend the recording time of a few data channels. If two, four or seven data signals are all that are to be recorded, a special sequencing circuit may be used in the following manner. The recorder is put into operation with the desired number of tracks being recorded. At the end of each pass, the recorder senses the end of usable tape, reverses the tape's direction and shifts the data signals to the next set of tracks. This operation continues until all tracks are used at which time the recorder turns itself off.

5.3.3 OVERLAP.

Overlap or recorder-to-recorder sequencing allows two recorders to be operated as one, continuously with no loss of data. As the running recorder reaches the "end-of-usable" tape, the waiting one starts and is up to speed as the running one shuts down. Tape is rethreaded on the now-waiting machine making it ready for the sequence signal from the running machine as it reaches the "end-of-usable" tape. Data signals are usually connected in parallel to both machines.

5.3.4 TAPE LOOP ADAPTER.

Tape loops are used for special instrumentation purposes. Loops can be associated with any type of capstan drive and can be a tensioned reversing-idler loop, a random bin loop, or a lubricated-tape circular loop. Loop adapters for conventional machines are available from some manufacturers. Storage from 5 feet to 150 feet is commonly available in most loop configurations. They are ideal where data analysis problems require continual replay of data into the analysis equipment or for any application that requires recording and continuously reproducing data without the necessity of stopping and rewinding tape.

5.3.5 SIGNAL ACTUATION.

As the name implies, a signal starts the recording operation by exceeding some preset threshold level. In the event the recorder cannot get up to speed in time to catch the signal, a tape loop machine may be used also. With the loop operating constantly, in the record, reproduce, erase sequence, and the loop delay between the record head and the reproduce head, the sudden appearance of a signal allows the loop-delay time for getting the data recorder up to speed. The signal is then dubbed to the data recorder from the reproduce head of the loop machine. Following the reproduce head on the loop machine, the tape is erased and the operation described above continues.

MAGNETIC TAPE

About thirty years ago recording tape was a paper ribbon coated with a crude red oxide material similar to red barn paint. Today's tape is a thin ribbon of plastic, usually polyester (Mylar*), on which an emulsion of highly refined magnetic oxides is placed. The binder, necessary to retain the oxides, also contains a variety of chemicals to reduce friction, improve the wetting characteristic of the oxide particles, reduce static charge, lubricate the tape, etc. The tape backing or web is manufactured in wide (usually 24- to 26-inch) continuous rolls, and after the binder (containing the oxide) is coated on the web and cured, is slit into the desired tape widths by precision slitting machines.

An instrumentation tape must have a very uniform overall thickness and a very close tolerance on width. Normally, the width tolerance (also known as the slitting tolerance) is +0.000 and -0.004 inch. The coating should not rub off onto the heads or stick to other portions of the tape transport mechanism, even at high tape speeds. Oxide particle distribution must be constant throughout the thickness of the oxide layer as well as the length of the tape. Oxide particle size and magnetic characteristics must be extremely well controlled for tapes that are to be used in very short wavelength reproduction.

The mechanical characteristics of a tape are governed by the base material. A tape base of polyester will exhibit the following properties:

1. Its moisture absorption is the lowest of all base materials and, therefore, it will not exhibit layer-to-layer adhesion in moist climates.

2. Its fungus resistance is excellent while that of a cellulose compound is exceedingly poor.

3. It is usable over an extremely wide temperature range; from -60° to 150° C.

4. Its dimensional stability makes it far superior to any of the other base materials.

The major disadvantage of polyester is that it will stretch rather than break when stressed beyond its yield strength. If this should occur the entire portion of tape, and the data it includes, must be discarded. Present day tape transports handle tapes very gently however, and stretching is quite uncommon unless the transport is out of adjustment. As a result, polyester bases are almost universally used on instrumentation machines because the cost differential is quite small in relation to the value of the data to be recorded.

6.1 TYPES OF TAPE.

The question of which tape to use for any specific application has consistently posed a problem for the users of Instrumentation Tape Recorders. Optimum performance for any machine is usually specified using a particular type of tape, and the use of other tape can seriously affect the machine's ability to operate at the manufacturer's specifications. Although Appendix A only briefly discusses the three general classes of tape applicable to IRIG Systems, the IRIG Document 106-73 covers, in much more detail, the standard for 1/2 and 1-inch magnetic tape.

The problems of tape selection have been compounded with the advent of 1/4-inch Instrumentation Tape Recorders. Unlike the 1/2 and 1-inch tape, which are made mostly for instrumentation applications, the majority of 1/4-inch tape is made for use in audio equipment. Given the list of all available 1/4 inch tape, where a high quality instrumentation tape can cost ten times that of a lower quality audio tape, the selection of the proper tape for a particular application can become an economic as well as performance decision. The variables in the tape itself and how they can affect performance, although mentioned at various sections throughout this primer, will be combined in the following guidelines for ease of reference.

1. Oxide Coating – Differences in oxide characteristics and coating thickness can cause up to an 8 db peak or dip in the frequency response of a recorder. The use of those types of tape for which the recorder was designed is the best method to minimize this problem.

2. Frequency Response – Instrumentation vs. audio tapes. For medium bandwidth recorders (up to .25 mil wavelength) quality audio tapes can be used with satisfactory results. However, variation in frequency response characteristics and output levels will cause performance of different types of tape to vary greatly. The audio tapes that do perform consistently well compared to instrumentation tapes are as expensive as the instrumentation tapes only they offer the advantage of being readily available at local retail stores. A significant disadvantage of audio tapes is that the important tape parameters are not specified or guaranteed by the manufacturer. The continued existence of a particular type of audio tape is a doubtful assumption in such a dynamic industry.

3. Effect on Head Wear – Some of the cheaper audio tapes do not use an adequate method to bind the oxide coating to the tape base material. The oxide which

---

*trademark of the Dupont Company

flakes off as a result causes excessive wear to both tape heads and guides. In light of the cost of replacing recorder heads, the expense of higher quality tape may well reduce the lifetime cost of heavily used machinery.

The majority of tapes use a ferrous oxide particle, while a harder more permeable chromium dioxide is used where higher frequency response is the main objective. The use of this chromium dioxide tape on machines having mu-metal heads rather than ferrite heads will cause a rapid increase in the rate of head wear.

Table 6-1 lists some of the tape types, their characteristics, and how they perform in comparison to each other. Although the higher quality tapes command a premium price, they are not the total answer to every measurement problem. Instrumentation recorders which specify audio tape to meet published specifications are commercially available and should be considered in any analysis which is undertaken.

6.2 SIGNAL DROPOUTS.

A universal problem in direct record instrumentation recording is signal dropouts. A dropout is defined as a 50 percent (or greater) amplitude reduction in the reproduced data. While generally caused by poor head-to-tape contact during the record or reproduce process they may also be caused by poor oxide particle distribution within the binder. The effects of poor head-to-tape contact may be reduced by cleaning the heads, guides and parts of the recorder that the tape contacts; but there is nothing the user can do about a tape that has poor oxide distribution or a rough surface.

The signal attenuation resulting from poor contact (or a rough tape surface) between tape and the head is most pronounced in the shorter wavelengths while absence of magnetic material in the binder affects all frequencies. The effect of poor head to tape contact is illustrated by the following formula and is termed spacing loss.

$$\text{Drop in playback level (db)} = 54\,\frac{d}{\lambda}$$

where d = separation of tape from head in inches

λ = recorded wavelength in inches

Table 6-1. Tape Characteristics

TYPE PARAMETERS	AUDIO		INSTRUMENTATION		
	LOW COST	HIGH COST	MEDIUM BAND	WIDE BAND	CHROMIUM DIOXIDE
Head Wear Characteristics	Highly Abrasive	Low	Low	Very Low	High
Minimum Recorded Wavelength (λ) *	$\lambda > .25$ mil only	$\lambda > .25$ mil only	$\lambda > .25$ mil only	$\lambda > .0625$ mil	$\lambda > .0625$ mil
S/N @ $\lambda > .25$ mil	Poor	Good	Good	Poor to Good	Excellent
S/N @ $\lambda < .25$ mil	Poor	Poor	Poor	Good	Good
Reliability of Tape Performance	Poor	Poor	Good	Good	Good

* Frequency = $\frac{\text{Tape Speed}}{\lambda}$

Figure 15 shows attenuation as a function of the separation-to-wavelength ratio. This is a universal curve; applicable to any speed, frequency and separation. It should be noted that Figure 15 illustrates the loss in signal level in playback only, assuming that the head and tape make adequate contact during recording. Obviously a similar signal loss will occur if there is tape/head separation at the record head during the record process. In addition to such frequency dependent losses, very high bias frequencies are perturbed by spacing loss to the extent that all frequency components of a data signal will suffer attenuation or distortion.

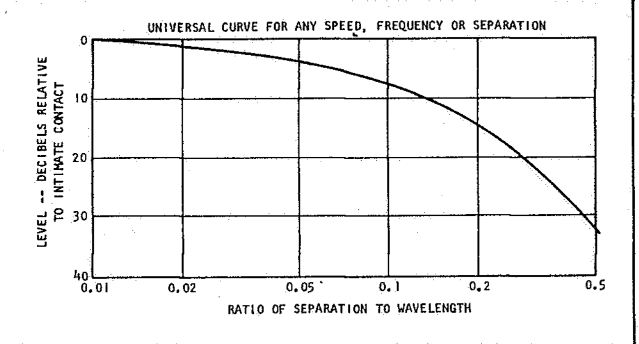


Figure 15. Signal Attenuation Caused by Poor Tape-to-Head Contact in Playback

In the playback of a low frequency signal of 15 mil wavelength, a separation of 1 or 2 mils affects the level only slightly, but at a high frequency of 1 mil wavelength, even a half-mil spacing results in a drop of more than 20 db. (A 1 mil wavelength results when one records 15,000-Hz at 15-ips, 60,000-Hz at 60-ips, etc.). In instrumentation recording, a 6 db or 50% drop in signal is considered critical. With a 1 mil wavelength, this takes place with 111 microinches (0.111 mil head-to-tape separation). Since a dust particle might easily approach this size, the possibility of spacing loss and the importance of keeping the recorder extremely clean is obvious. When the heads are not cleaned for extended periods of time, complete loss of high frequencies can easily occur; and every other part of the recorder may be blamed before the heads are finally cleaned.

6.3 HANDLING OF MAGNETIC TAPE.

When tape is handled, as during splicing, the operator's hands should be thoroughly clean to prevent contamination of the tape by body oils and salts which will cause the tape, once contaminated, to pick up foreign particles. The use of sticky masking tape or cellulose ("Scotch cellophane") tape as splicing or tail-end hold-down is strongly not recommended. Small deposits of the adhesive will stick to the tape.

Heads and guides should be cleaned to remove accumulations of foreign matter each time a tape is placed on a recorder. The machine manufacturer's recommended cleaning procedure should be followed. If extreme importance is placed on the data to be recorded, it should be remembered that a tape which has been run through the transport several times will have fewer dropouts than a new one, due to the resulting polishing or smoothing action.

6.4 CLEANING.

If there is difficulty with signal dropouts arising from contamination by dust, carefully wipe the surface and backing of the tape with a lint-free cloth, such as a very soft chamois. To get rid of contamination that does not brush off easily, use a cloth slightly moistened with Freon TF. Aliphatic hydrocarbon type solvents (heptane, gasoline, naptha) can also be used, but care should be exercised because they are flammable. Freon TF is non-toxic and non-flammable. Do not use carbon tetrachloride, ethyl alcohol, trichlorethylene, or other unknown cleaning agents because they may soften the oxide, deform the backing or both.

6.5 STORAGE.

When not in use, tapes should be placed on a precision reel, uniformly wound at a moderate tension, and then given protected storage. Recommended takeup tension for most instrumentation recorders using 1 mil tape is 4 to 5 ounces for each 1/4-inch of tape width. The best method of storage is to place the reel of tape in a self-sealing plastic case and to store it on edge in a storage bin equipped with partitions between each reel. The plastic case protects tape from dust and sudden humidity and temperature changes. It also guards both tape and reel from damage in handling when the tape is transported between work and storage areas. The plastic envelope and cardboard box in which tape is supplied will probably find much more use than special containers and is reasonable protection under all but the worst conditions.

If the tape must be stored in the presence of magnetic fields, either ac or dc, special containers are available. These will protect the data from erasure under all but extremely high fields. However, it is more desirable to store away from the field if at all possible.

Extremes of temperature and humidity should be avoided. In general, recommended storage conditions for both types of base are as follows:

Relative humidity:	40 to 60%
Temperature:	60 to 80° F

If extremes in temperature are encountered during the storage or transit, tape should be brought to equilibrium before it is used. Assuming, for instance, that a tape has been in storage or transit at sub-zero temperatures, it should be stored for a minimum of 4 to 8 hours at room temperatures before it is used. Actually, it will not regain complete equilibrium for approximately 16 hours. This time can be shortened by accelerating temperatures, but these temperatures should not exceed 100°F; otherwise, condensation will form on the tape, which may prove to be a problem. Avoid using direct heat, such as from lamps or other spot heaters to warm up a tape.

Temperature and humidity conditions during shipment are unpredictable, especially when shipment is made by air. Temperature and humidity vary so rapidly on take-off that the stresses across (or through) the tape pack do not reach equilibrium before these conditions reverse during landing. Uneven stretching across the width of the tape results in edge ruffles when the tape is reproduced. Thermally insulated plastic containers, taped at the edges, reduce the effect of temperature and humidity shock and depending upon the time of the flight, the tape should be allowed to reach temperature equilibrium as described in the previous paragraph. Procurement of hermetically sealed tape shipping cartons may be necessary if the ultimate in tape safety is required.

If the tape has been subjected to combinations of temperature and humidity which cause between-layer sticking, it may be beyond saving. Do not place the recorder in fast forward when unrolling a reel suspected of abnormal storage or transit conditions; instead use a low speed drive mode. All tapes that have been stored for long periods of time should be unrolled and rewound to ensure normal tape pack on the supply reel.

6.6 PHYSICAL DISTORTION.

While most signal dropouts in instrumentation recordings are caused by specks of dust and other contaminants which lift the tape away from the head, two other significant causes are dents and creases in the base material. Dents can be caused either by foreign particles becoming wound up tightly in the roll or by roughness in the surface of the hub on which the tape is wound. These may cause a permanent dent or crease in many layers of the tape which cannot be stretched out flat as the tape passes over the head. Stresses in the roll which are sufficient to stretch the backing 5 percent will generally leave a permanent impression. Stresses below the 5 percent point are not normally permanent. Creases usually are caused by handling the tape (i.e., threading, splicing, removing the tape from the guides, etc.) or by damage to the edges of the tape because of uneven winding.

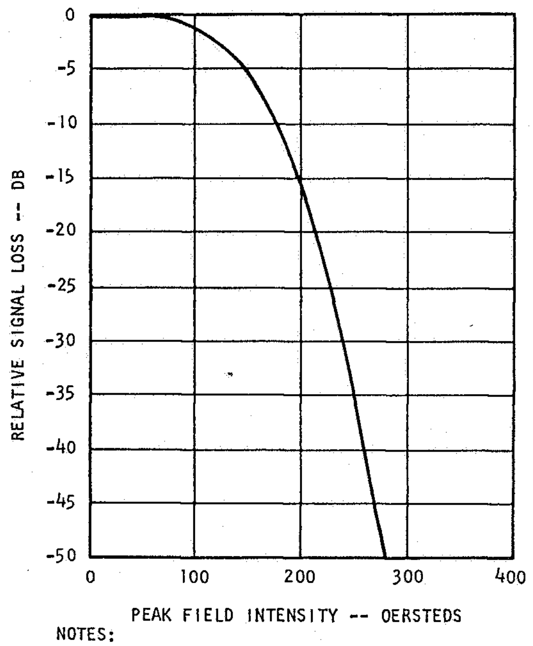
Most causes of distortion of the base material can be eliminated by the use of a precision reel. A typical precision reel has straight or tapered flanges which are accurately machined and spaced to minimize the scattering of turns during winding. The flange design also affords greatly increased protection against dust and crushing of the tape edges. The hub has no threading slots which cause distortion of the inner turns. Instead, it is often covered by a neoprene friction band to aid in threading. This ring acts as a cushion for the innermost tape layers and tends to minimize distortion from winding pressure and expansion-contraction stresses.

6.7 ERASURE OR SATURATION.

Magnetic properties of instrumentation tapes are stable indefinitely. Magnetic retentivity is permanent unless altered by magnetic means. It may be altered, for example, by magnetic fields from permanent magnets or electromagnets. These, very likely, will cause partial erasure if placed within a few inches of the tape.

This principle is used in the bulk erasing process in which a whole reel of tape is demagnetized without unwinding. The fields necessary to produce complete erasure, however, are so intense that it is not likely that stray magnetic fields will cause trouble of this kind. Complete erasure (considered for purposes of this discussion to be reduction of signal to a point below the noise level of the system) does not usually take place unless the field is strong enough to exert a noticeable attraction for the tape. Slight erasure can occur, however, without any noticeable attraction or vibration.

Figure 16 illustrates the relation between field intensity and erasure as shown in experiments conducted with a typical ac bulk eraser. Some erasure is noticeable at a field intensity of only 100 oersteds. A 6 db loss is generally considered critical because it represents a 50 percent reduction in signal strength. In some applications a loss of 1 db might be critical.



NOTES:

FIELD INTENSITY MEASURED AT CENTER OF RECORDED TRACK. TRACK WIDTH = 0.090 INCH. λ = 0.015 IN (500 CPS AT 7.5 IPS). 0 DB = 8 DB BELOW LEVEL FOR 3% HARMONIC DISTORTION.

Figure 16. Erasure as a Function of Field Intensity

Both unrecorded and recorded tapes should be kept away from electromagnetic bulk erasers and storage cabinets with magnetic latches. Unrecorded tapes should not be placed near dc magnetic fields, such as traveling-wave-tubes or magnetron magnets, because they may become heavily biased or even create gross distortion in the record process (i.e., the resultant signal-to-noise ratio will be reduced).

If parts of the recorder become magnetized, they can cause tape erasure, possible tape saturation and signal degradation. As a preventive measure, periodic demagnetization of critical parts, particularly heads, is recommended.

To guard against accidental erasure of recorded tape during shipment, tape can be packed with bulk spacing (such as wood) between the tape and its shipping carton. Bulk spacing is effective in reducing the possibility of accidental erasure by fields encountered during transit because field strength varies inversely with the square of the distance. Assuming that no field strength greater than 1000 oersteds would be encountered during shipment (this is unverifiable but a reasonable assumption), 3 inches of bulk spacing would give adequate protection.

The special shielded container described in the paragraph on storage may be used in shipment if large stray magnetic fields are expected during shipment. Experience, however, indicates that standard shipping cartons are usually satisfactory.

SPECIAL TECHNIQUES AND MISCELLANEOUS INFORMATION

7.1 PULSE CODE MODULATION (PCM).

Pulse code modulation is a method of coding digital data in the form of discreet pulses to enhance the transmission and recording of information in digital format. Instruments designed for or able to use a PCM format will normally use direct record and reproduce electronics. The wide bandwidth that direct offers allows successful recording of high density PCM data. The limitations of direct electronics at the low end of the frequency spectrum can present problems in the recording of dc levels associated with a continuous string of unchanged data bits (i.e., a long run of "O" level data). Of all the codes which exist to minimize these problems only a few distinctly different ones (see Table 7-1) are usually encountered in the recording industry.

7.2 PULSE RECORDING.

The use of instrumentation recorders to record radar-like, narrow pulse signals requires some compromises because these machines are largely optimized for analog (sinewave) recording.

The purpose of the following discussion is to understand the limitations of these compromises. Actually, reasonable pulse fidelity can be produced by the direct record/reproduce process, as well as in the wideband (dc-500 kc) FM record/reproduce method. Each method, while somewhat different in response, is affected by the same basic problem; the lack of high or low frequency response.

Much too often, recorded pulses are buried in the recorder system's noise even though they enjoyed several db of signal-to-noise ratio when they left the receiver. One or more of the following factors can contribute to this.

7.2.1 SYSTEM NOISE NOT MINIMIZED.

Noisy tape. The use of virgin tape does not guarantee minimum tape noise. In the normal handling of magnetic tape from manufacturer to the recording site, the noise or "hiss" level may increase by several db because of stray magnetic fields encountered enroute. Inadequate erasure or degaussing can increase the tape noise level if the tape is reused. If there is a doubt concerning the residual noise level on a given reel of tape, several spot checks should be made by reproducing the unrecorded tape with a "standardized" reproduce gain setting. Actually, relative levels between reels are all that is important here, and the criteria may be set by the level produced from a virgin or carefully degaussed tape.

Magnetized record or reproduce heads. Magnetized record or reproduce heads will increase the noise level of the reproduced signals. Head demagnetization should be done weekly on a routine maintenance schedule and whenever system noise appears to increase.

While not affecting the signal on the tape, noisy reproduce circuitry can degrade pulse type data reproduction. Noisy tubes or components may cause this degradation and careful selection of tubes, transistors, or components to replace the noisy ones may improve the performance significantly.

7.2.2 IMPROPER BIAS LEVEL.

Many tape recorder instruction books outline a specific procedure for setting the proper value of bias and signal current through each record head winding. Some specify a nominal value, others rely on the shape of the output waveform. Unfortunately, neither method is foolproof.

A nominal value of bias current, especially in wideband recording, does not ensure maximum performance. Optimization of the bias while reproducing a square wave, ensures maximum performance, based of course, on the assumption that the reproduce (and equalizer) circuitry is properly adjusted.

If pulse signals are to be reproduced on a machine capable of phase equalization adjustment, tapes on which pulse type data is to be recorded should be biased for a flat (±3 db) sinewave response (including pre-emphasis); i.e., no changes should be made in the bias adjustment from the sinewave case. In the past, it was observed that changes in bias setting apparently resulted in better pulse recordings: it was found however, that even higher fidelity pulse waveforms could be recorded and reproduced by optimizing only the equalizer adjustments for pulses and leaving the bias set as recommended for sinewave recording.

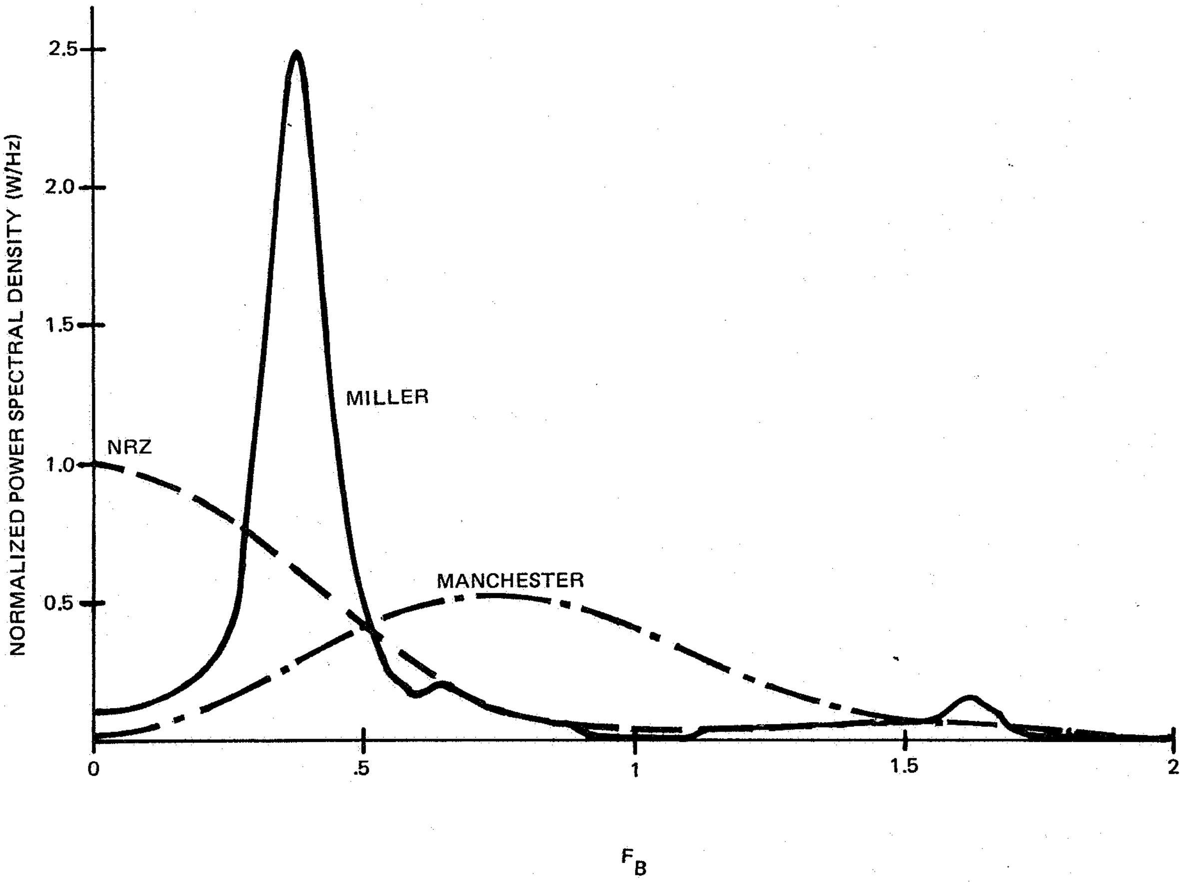
7.2.3 RECORDING LEVEL IMPROPERLY SET.

The proper record level setting for any signal is that setting which best matches the dynamic range of the signal to the dynamic range of the recorder. The dynamic range of the recorder is defined as that range between the amplitude of a signal at a rather arbitrary value of harmonic distortion (usually somewhere between 3% and 1% total) and the amplitude of the reproduced system noise. Because pulse type signals are unidirectional, the dynamic range realized when recording them is 6 db less than for sinewave signals; assuming the same harmonic distortion. This means that the peak-to-peak value of a pulse type signal must be reduced to one-half (6 db) the peak-to-peak value of a sinewave signal. If not, higher distortion will result. Pulse signals, however, tolerate more harmonic distortion than sinewave signals for the same apparent fidelity.

Table 7-1. PCM Code Comparison

CODE	REQUIRED LOW FREQ. (SINEWAVE) RESPONSE*	REQUIRED HIGH FREQ. (SINEWAVE) RESPONSE*	CLOCK SIGNAL EXTRACTION	PACKING DENSITY	BIT ERROR RELIABILITY
NRZ	DC	3/4 The Bit Rate	Timing Error Must Be < ±1/2 Bit Cell	> 6k Bit Per Inch Per Channel	> 1 in 10^6
Bi ϕ (Manchester)	1/5 The Bit Rate	1.4 Times The Bit Rate	Self Clocking	> 12k Bit Per Inch Per Channel	> 1 in 10^6
DM (Miller)	1/10 The Bit Rate	3/4 The Bit Rate	Self Clocking	> 20k Bit Per Inch Per Channel	> 1 in 10^6

*



F_B = Normalized bit rate in bits/second.

$$F_B = DS$$

D = Packing density in bits/inch.

S = Tape speed in inches/second.

F_C = Suggested upper band edge cut-off frequency.

$$F_C = .75\ F_B$$

7.2.4 PULSE RESPONSE.

The pulses referred to in the preceding information are assumed to be 1 to 10 microseconds wide and occurring at rates from 100 to 4000 pulses per second. Occasionally, it is desirable to record pulses having higher or lower widths and rates. A rule of thumb for direct record recorders says "The recorder must have a sinewave frequency response ten times the frequency of the square wave to reproduce an acceptable rise time and one tenth the frequency of the square wave to reproduce an acceptable droop characteristic", i.e., a 1.0-MHz machine will reproduce a 100-kHz square wave or pulse equivalent with a good rise time; and a machine recording to 300-Hz will reproduce a 3000-Hz square wave with a good droop characteristic. If longer pulses must be recorded, and rise time requirements are not too stringent, wideband (db to 500-kHz) FM may be used. This method of recording pulses produces excellent low frequency performance, good signal-to-noise ratios, and good pulse fidelity at somewhat reduced rise time response.

Best pulse recordings will be made when careful adjustment of bias and record level is made while observing the output of the reproduce amplifiers (assuming they have been optimized for square wave or pulse response). This operation is usually referred to as "downstream monitoring" and is most effective to ensure good recordings.

7.2.5 RECORDING PULSES FROM RECEIVERS.

A signal from a receiver equipped with AGC can usually be handled by the recorder's dynamic range with little difficulty if the receiver noise is set to record a few db above the inherent recorder system noise level. Unfortunately, AGC derives its control from all signals in the pass band and a very strong interfering signal can desensitize the receiver to the point where a weaker signal is wiped out. If the weaker signal is to be recorded, manual gain control must be used. If the difference in level between the interfering signal and the signal of interest then exceeds the dynamic range of the recorder, a good recording cannot be made.

A somewhat different problem arises when recording the output of a scanning receiver because this type of receiver's noise level will usually vary several db as the receiver is tuned or scanned through its range. To record a scanning receiver output, the record level must be set to record the minimum receiver noise just above the recorder's system noise. This may make the recording more susceptible to saturation, but is probably the most acceptable compromise.

The only sure way to make a good recording of a signal which has a large variation in amplitude is to "ride the gain", much as is done in broadcast and recording studios. This would appear to be an impossible additional task to impose on the operator, but whenever a received signal is viewed on an oscilloscope by the receiver operator and necessary adjustment of the receiver gain made, prolonged overload of the recorder can usually be prevented. To do this, the signal amplitude which causes saturation in the recorder should be referenced (with a grease pencil) on the face of the oscilloscope during the pre-operation setup. When this level is exceeded, the operator can adjust the receiver gain to lower the signal amplitude. A little effort expended in this manner can ensure proper record levels a high percentage of time.

NOTE

> Receiver gain adjustments during an operation may be contrary to the system operational doctrine. Be sure to check before employing this technique.

Monitoring of the record level during an operation will often not be practical or possible. Special care in the pre-operation setup, however, will still provide usable recordings. It should be remembered that most signals must be recorded right down to the receiver's noise as their levels fluctuate. The receiver noise, therefore, must be recorded above the recorder's system noise. If large variations in signal level are expected, saturation of the recorder and consequent distortion may be expected, but this is probably more desirable than losing a weak signal. Actually, saturing a recorder is a rather gradual process. A signal that is 10-db above normal record level will add only a few percent to the distortion. The process is not like that of a saturated amplifier, where a well defined clipping level is reached. True, saturation will lengthen pulses and can make two closely spaced pulses look like one, but this is usually preferable to missing the weak signal. Analytic methods may recover signals recorded when the equipment was operated in an occasional saturated condition, but pulses buried in the noise may never be recovered. Recovery to normal recorder operation from a saturated condition is quite rapid, usually only a few microseconds.

Saturation, as discussed above, refers to the actual magnetic saturation of the tape. In some recorders, the record amplifier seems to saturate before the tape. Longer recovery time and greater distortion can result in this case.

7.2.6 RECORDER ADJUSTMENTS.

To record pulses properly, the machine must be kept in excellent condition. A rigid maintenance and adjustment schedule must be followed. Heads must be kept clean and demagnetized, tension adjustments must be checked often, and tapes must be handled carefully.

Careful attention to the foregoing factors will enable good recordings of pulses on the tape, but there is a possibility of pulse degradation occuring during the reproduce operation. Some recommended equalizer adjustments result in essentially an underdamped filter. Pulses through such an equalizer will cause large overshoots and ringing. Equalizer adjustment which gives a critical damped characteristic will reduce these distortions. Further reduction can be obtained if the machine also provides for phase equalization, which, rather than affecting the frequency response, affects the phase response; i.e., keeping the spectral components of the pulse in the proper time relationship. Reproduce equalizers with phase response adjustments, once optimized for pulses, do not require readjustment for sinewave use.

It is assumed that the reproduce amplifier's output control has been set to produce an output level similar to that described in the manufacturer's manual. Some reproduce amplifiers can themselves be saturated by large signals from the tape, even though the tape is not saturated. Avoid this condition at all times.

Gross differences between the many different recorders, and even the subtle differences between each track of the same recorder, preclude the listing of standardized settings for pulse recording. The purpose of this section has been to emphasize that the manufacturer's recommended setup procedure is not necessarily optimum for pulse recording. It is certainly the place to start from, but the best settings can only come from "downstream monitoring" the result of each adjustment as it is made.

7.3 PREDETECTION RECORDING.

A data collecting-receiving system may be required to process many types of modulated signals, e.g., FM/FM, PDM/FM, PCM/FM, PAM/FM, SSB/FM, FSK, FM, PPM, PAM and AM. The bandwidths of these signals vary from a few hertz to several megahertz. Information may be in a single channel or multi-channel form on one carrier.

It is in such systems that predetection recording has been used to great advantage. Signals recorded in this fashion may be played back for off-line (non-real-time) data reduction. Less signal processing equipment is required for this since a single demodulation system can be used sequentially on several tracks of predetected signals. Also, if the demodulation process must be optimized, or refined, successive demodulations may be made until the best results are obtained.

In a typical predetection recording system the receiver IF amplifier signals are translated down a frequency band compatible with a wideband, direct record, instrumentation recorder (usually in the range of 100-kHz to 1.5-MHz). Such a signal still retains the original modulation if not restricted by recorder bandwidth. When reproduced, this data can be detected and reduced directly or it may be translated up to a higher frequency (usually the original IF frequency) for the data reduction operation.

The major use of predetection recording is in missile range applications where multichannel telemetry is used to simultaneously monitor the many transducers installed for the test or flight. The major advantage of predetection recording in this application is that one track of the recorder can hold many channels of data. This greatly simplifies the receiver site equipment and also permits better control over the demodulating and demultiplexing of the data.

As an example of predetection recording, suppose the entire standard broadcast band (560–1640-kHz) were recorded on a wideband instrumentation recorder. When reproduced, a conventional broadcast receiver could be used to tune in any station that was on the air at the time the recording was made.

It is natural to try to use predetection recording instead of post-detection recording for signals of unknown characteristics since there is a strong possibility that the detection process may be something less than optimum. In short, the quality of the data from a post-detection recording of an unknown signal is subject to the accuracy of a one-shot field judgement made by the operator. However, there must be an understanding of the limitations of predetection recording if it is to be used with success.

Contrary to the normal detected receiver signal, undetected signals can have a wide dynamic range (60 to 90-db), especially in receivers used for surveillance work. The wideband recorder, in direct record mode, has about 20 to 25 db dynamic range. In predetection recording systems used on missile ranges, the receiver frequency translator, and range telemetry transmission characteristics are arranged to match the recorder's capability. In dealing with surveillance activities, however, one does not have this sort of control and needs the wide dynamic range offered by the receiver. The capability given up by matching the dynamic ranges of the receiver and the recorder will probably destroy some signals, especially if the signal-to-noise is low or if strong interfering signals exist in the receiver passband.

All telemetry systems employing predetection recording use a frequency-modulated carrier transmission link. As recorded on the tape, this FM signal is relatively insensitive to the amplitude instability encountered in a typical instrumentation recorder since the information is in the signal zero crossings, not the signal amplitude. However, any signal containing information in its amplitude will be seriously distorted by the amplitude instabilities normally encountered in the direct record process. These include drop-outs, variations in response of the magnetic material on the tape, spacing loss during record, etc. All of these effects occurring in either record or reproduce can give grossly erroneous results on AM data.

The bandwidth of the recorder used for predetection recording is usually 100-kHz to 1.5-MHz. Frequencies below 100-kHz are not used for the wideband predetection signal as distortion due to spectrum fold-over will occur in the up conversion process. The recorder therefore limits the bandwidth of the signal that can be recorded by the predetection method. If signals of wider bandwidth are received and recording is attempted, distortion products will occur which will thoroughly confuse the data reduction process.

Flutter or time displacement error affects predetection recording as it does any detected signal recording. Especially deleterious to FM signals, flutter may be compensated for to some degree by either electronic or capstan drive servo techniques, whichever is most applicable.

The discussion just presented has assumed that a longitudinal recorder is used which offers a flat (±3-db) response from 1-kHz to 1.5-MHz at 120-ips. This type of recorder is 7 or 14 channel and is universally used in instrumentation work. If one need record only one channel of data by predetection, the transverse or "spinning head" recorder provides up to 5-MHz of bandwidth. The use of this machine reduces the effects of dropouts and spacing loss as the data is recorded by FM carrier means. Bandwidth is much greater and higher center frequencies may be used to record a wider band of data on the tape. Flutter and TDE are very low; TDE in the range of ±25 nanosecond. Dynamic range is somewhat better (typically 38-db) than longitudinal recorders, but the cost per channel is much higher and the machine is considerably more complex, especially to maintain.

Predetection recording is a useful instrumentation technique as long as its limitations are understood and observed. If predetection recording limitations are ignored, very misleading data can be generated.

7.4 DUBBING.

Since a tape recording must frequently be used for analysis in different locations, duplicate tapes are made. The process of duplicating the master tape is known as "dubbing". Several important considerations must be made when dubbing:

1. Both recording and reproducing machines should be of equal or better quality than the original recorder.

2. Both machines must have the same track format as the original recorder.

3. If the reproducing machine has a wider bandwidth than the original recorder, improved high-frequency response may be obtained, but reduced signal-to-noise ratios will likely result from the wider bandwidth. Specific signal parameters can be optimized by proper selection of the reproduce equalization.

4. Flutter characteristics of both the original machine and the two machines doing the dubbing will affect the dubbed recording. As a result, flutter-affected parameters will always be more obvious in the dub than on the original tape.

5. The output levels of the reproduce machine must be carefully matched to the input of the record amplifiers of the record machine. When optimally set, the dub will be at least 3-db less than the original in signal-to-noise ratio.

6. Recordings made with FM carrier recording electronics may be dubbed by the direct recording process. However, tests indicate that even though unsupported by theory, better results can be obtained when the FM recorded data is demodulated in the normal manner and re-recorded on an FM recording machine.

APPENDIX A

IRIG AND ITS STANDARDS

A brief overview of what IRIG is and how the standards came to be established was discussed in paragraphs 1.3 and 2.1.4. This appendix contains other information regarding some of the specifics of the IRIG standard and the tables referenced throughout this primer.

A.1 RECORDER HEADS.

Over the years, the IRIG standards have obtained a standardization in track and head geometry which guarantees compatibility between instrumentation tape recorders, i.e., tapes recorded on one manufacturer's machine will play back on another. IRIG 106-73 contains the latest details and only some of the highlights will be mentioned here. Track width shall be 0.050 inch, track-to-track spacing shall be 0.070 inch center-to-center, seven tracks will be used on 1/2-inch tape and 14 tracks on 1-inch tape. The tracks, as a group, will be centered on the tape, i.e., on 1/2-inch tape track #4 will be located in the center of the tape, etc. Standard head placement is to locate the heads for alternate tracks in separate head stacks. Thus, to record all tracks of a standard width tape, two record head stacks are required and to reproduce all tracks, two reproduce head stacks will be used. The two stacks of a record (or reproduce) pair shall be mounted such that the center lines through the head gaps of each stack are parallel and shall be spaced 1.500 (±0.001) inches apart as measured along the tape path. The alignment of individual gaps within a head stack shall be within ±1 minute of arc referenced to a straight line perpendicular to the direction of tape travel in the plane of the tape.

Until recently, IRIG has had trouble imposing its track numbering standard. For many years there was both an IRIG standard and an Ampex standard. The IRIG standard numbers the tracks 1 through 7 (14) from left to right as you look down the tape in the direction of travel, on the oxide side. Thus track #1 is the first track on the left in the first head stack. The second head stack contains all the even numbered tracks with track 6 (14) on the right edge. This standard prevails for all recorders (including Ampex) manufactured in the last few years. The Ampex track numbering standard was widely used at one time however, and some recorders using the Ampex format are no doubt still in use. The Ampex standard numbers the tracks 1 through 7 (14) from right to left as you look down the tape in the direction of travel, on the oxide side. Thus, track 1 is the first track on the right in the first head stack. The second head stack contains all the even-numbered tracks with track 6 (14) on the left edge.

Only in a few isolated instances will a tape recorded in one format be reproduced by a machine with the other format, but an unusual problem arises when this occurs. Track spacing and track width are the same for both formats, thus each recorded track will be reproduced; but recorded track 1 will reproduce as track #14, track #2 will reproduce as track #13, etc. At first glance, a simple translation in the numbering of the reproduce amplifiers would seem to clear up the confusion. Unfortunately, there is a serious inter-track timing error which arbitrary numbering of the outputs won't cure. This incompatibility occurs in the following manner: The even-numbered tracks are recorded by the #2 head stack at a point 1.5-inches "downstream" from the odd-numbered tracks (either format). When reproduced with head stacks of the opposite format, the even-numbered recorded tracks are reproduced by the #1 head stack, and 3 inches (2 x 1.5 inches) of additional tape travel is necessary to get the time-coincident data of the odd-numbered recorded tracks beneath the #2 reproduce head stack. At 60-ips tape speed, a 50-millisecond delay plus twice the usual stack-to-stack timing inaccuracies is incurred by all data originally recorded on odd-numbered tracks in relation to the data which was recorded on even-numbered tracks.

A.2 TYPES OF TAPE.

There are three general classes of tape available today. The wideband tapes, which are used for recording wavelengths as short as 80 microinches (1.5-MHz at 120-ips), a medium grade tape for wavelengths as short as 240 microinches (0.5-MHz at 120-ips), and a standard grade tape for wavelengths as short as 600 microinches (100-kHz at 60-ips). As may be expected the price varies quite proportionally with the ability of the tape to reproduce short wavelengths.

Table A-1. IRIG Direct-Record Parameters

TAPE SPEED (IPS)	±3 DB PASS BAND (HZ*)	RECORD BIAS SET FREQUENCY (KHZ)	RECORD LEVEL SET FREQUENCY (KHZ)
Low Band		(overbias 3 db**)	
60	100 – 100,000	100	10.0
30	100 – 50,000	50	5.0
15	100 – 25,000	25	2.5
7-1/2	100 – 12,000	12	1.2
3-3/4	100 – 6,000	6	0.6
1-7/8	100 – 3,000	3	0.3
Intermediate Band		(overbias 3 db**)	
120	300 – 500,000	500	50.0
60	300 – 250,000	250	25.0
30	200 – 125,000	125	12.5
15	100 – 60,000	60	6.0
7-1/2	100 – 30,000	30	3.0
3-3/4	100 – 15,000	15	1.5
1-7/8	100 – 7,500	7.5	0.75
1.5 Wideband		(overbias 1 db**)	
120	400 – 1,500,000	1,500	150
60	400 – 750,000	750	75
30	400 – 375,000	375	37.5
15	400 – 187,000	187	18.7
7-1/2	400 – 93,000	93	9.3
3-3/4	– 46,000	46	4.6
2.0 Wideband		(overbias 2 db**)	
120	400 – 2,000,000	2,000	200
60	400 – 1,000,000	1,000	100
30	400 – 500,000	500	50
15	400 – 250,000	250	25
7-1/2	400 – 125,000	125	12.5
3-3/4	400 – 62,500	62.5	6.25

* Passband response reference is the output at the record level set frequency.

** Using an input signal level 5 to 6 db below normal record level, the record bias current is adjusted for maximum reproduce output and then increased until an output of the indicated db level below the maximum value is obtained.

Table A-2. IRIG Single-Carrier and Wideband FM Record Parameters

LOW BAND	TAPE SPEED IPS (MM/S) INTERMEDIATE BAND	WIDEBAND GROUP I	CARRIER DEVIATION LIMITS*				
			CARRIER CENTER FREQUENCY (KHZ)	CARRIER PLUS DEVIATION (KHZ)	CARRIER MINUS DEVIATION (KHZ)	MODULATION FREQUENCY (KHZ)	RESPONSE AT BAND LIMITS (DB)***
1-7/8 (47.6)			1.688	2.363	1.012	DC to 0.313	±1
3-3/4 (95.2)	1-7/8 (47.6)		3.375	4.725	2.025	DC to 0.625	±1
7-1/2 (190.5)	3-3/4 (95.2)		6.750	9.450	4.050	DC to 1.250	±1
15 (381)	7-1/2 (190.5)	3-3/4 (95.2)	13.50	18.90	8.100	DC to 2.500	±1
30 (762)	15 (381)	7-1/2 (190.5)	27.00	37.80	16.20	DC to 5.000	±1
60 (1524)	30 (762)	15 (381)	54.00	75.60	32.40	DC to 10.00	±1
	60 (1524)	30 (762)	108.0	151.2	64.80	DC to 20.00	±1
	120 (3048)	60 (1524)	216.0	302.4	129.6	DC to 40.00	±1
		120 (3048)	432.0	604.8	259.2	DC to 80.00	±1
		WIDEBAND† GROUP II**					
		3-3/4 (95.2)	28.125	36.562	19.688	DC to 12.50	±1, -3
		7-1/2 (190.5)	56.250	73.125	39.375	DC to 25.00	±1, -3
		15 (381)	112.50	146.25	78.750	DC to 50.00	±1, -3
		30 (762)	225.0	292.50	157.50	DC to 100.0	±1, -3
		60 (1524)	450.0	585.00	315.00	DC to 200.0	+1, -3
		120 (3048)	900.0	1170.0	630.0	DC to 400.0	+1, -3

* Input voltage of 1.0 to 10.0 volts peak-to-peak shall be adjustable to produce full frequency deviation.

** The second group of wideband FM carrier frequencies are primarily for use with predetection recorders where one or more FM analog channels are also required.

*** Frequency response referred to 1 kHz output for FM channels 13.5 kHz and above and 100 Hz for channels below 13.5 kHz.

† Wideband FM recording systems, as defined by IRIG, can only be used on recorders with 1.2 MHz (or greater) direct record response at 120-ips. As shown in the table, center frequencies have been established for tape speeds from 3-3/4 to 120-ips, with a deviation ratio and deviation of 0.675 and 30 percent respectively. These low values of deviation ratio and percentage deviation greatly reduce the system's signal-to-noise ratio. Quoting from the IRIG document, "The signal-to-noise ratio for a signal of 0.1 maximum modulation frequency listed in Table A-2 recorded at full deviation shall be 25 db minimum for tape speeds 15-ips and above, and 22 db minimum for tape speeds below 15-ips." Direct recording with ac bias is used to record the wideband FM signal since distortion products cannot be kept "out-of-band". Even so, quite a bit of sophistication is necessary to produce octave bandwidth voltage controlled oscillators and discriminators. Hardware to implement this type of recording has primarily come from the telemetry ground equipment manufacturers as a more or less natural extension of their art.

Table A-3. IRIG Proportional Subcarrier Channels

Channel	Center Frequencies (Hz)	Lower Deviation Limit* (Hz)	Upper Deviation Limit* (Hz)	Nominal Frequency Response (Hz)	Nominal Rise Time (msec)	Maximum Frequency Response** (Hz)	Minimum Rise Time** (msec)
±7.5% CHANNELS							
1	400	370	430	6	58	30	11.7
2	560	518	602	8	42	42	8.33
3	730	675	785	11	32	55	6.40
4	960	888	1,032	14	24	72	4.86
5	1,300	1,202	1,398	20	18	98	3.60
6	1,700	1,572	1,828	25	14	128	2.74
7	2,300	2,127	2,473	35	10	173	2.03
8	3,000	2,775	3,225	45	7.8	225	1.56
9	3,900	3,607	4,193	59	6.0	293	1.20
10	5,400	4,995	5,805	81	4.3	405	.864
11	7,350	6,799	7,901	110	3.2	551	.635
12	10,500	9,712	11,288	160	2.2	788	.444
13	14,500	13,412	15,588	220	1.6	1,088	.322
14	22,000	20,350	23,650	330	1.1	1,650	.212
15	30,000	27,750	32,250	450	.78	2,250	.156
16	40,000	37,000	43,000	600	.58	3,000	.117
17	52,500	48,562	56,438	790	.44	3,938	.089
18	70,000	64,750	75,250	1050	.33	5,250	.067
19	93,000	86,025	99,975	1395	.25	6,975	.050
20	124,000	114,700	133,300	1860	.19	9,300	.038
21	165,000	152,625	177,375	2475	.14	12,375	.029
±15% CHANNELS***							
A	22,000	18,700	25,300	660	.53	3,300	.106
B	30,000	25,500	34,500	900	.39	4,500	.078
C	40,000	34,000	46,000	1200	.29	6,000	.058
D	52,500	44,625	60,375	1575	.22	7,875	.044
E	70,000	59,500	80,500	2100	.17	10,500	.033
F	93,000	79,050	106,950	2790	.13	13,950	.025
G	124,000	105,400	142,600	3720	.09	18,600	.018
H	165,000	140,250	189,750	4950	.07	24,750	.014

* Rounded off to nearest hertz.

** Indicated maximum data frequency response and minimum rise time are based on the maximum theoretical response that can be obtained in a bandwidth between the upper and lower frequency limits specified for the channels.

*** Channels A through H may be used by omitting adjacent lettered and numbered channels. Channels 13 and A may be used together with some increase in adjacent channel interference.

Table A-4. IRIG Constant-Bandwidth FM Subcarrier Channels

A CHANNELS		B CHANNELS		C CHANNELS	
Deviation Limits = ±2 kHz Nominal Frequency Response = 0.4 kHz Maximum Frequency Response = 2 kHz*		Deviation Limits = ±4 kHz Nominal Frequency Response = 0.8 kHz Maximum Frequency Response = 4 kHz*		Deviation Limits = ±8 kHz Nominal Frequency Response = 1.6 kHz Maximum Frequency Response = 8 kHz	
CHANNEL	CENTER FREQUENCY (KHZ)	CHANNEL	CENTER FREQUENCY (KHZ)	CHANNEL	CENTER FREQUENCY (KHZ)
1A	16				
2A	24				
3A	32	3B	32	3C	32
4A	40				
5A	48	5B	48		
6A	56				
7A	64	7B	64	7C	64
8A	72				
9A	80	9B	80		
10A	88				
11A	96	11B	96	11C	96
12A	104				
13A	112	13B	112		
14A	120				
15A	128	15B	128	15C	128
16A	136				
17A	144	17B	144		
18A	152				
19A	160	19B	160	19C	160
20A	168				
21A	176	21B	176		

* The indicated maximum frequency is based upon the maximum theoretical response that can be obtained in a bandwidth between deviation limits specified for the channel. (See discussion in Appendix B for determining practical accuracy versus response tradeoffs.)

APPENDIX B

HEWLETT-PACKARD INSTRUMENTATION MAGNETIC TAPE RECORDING SYSTEMS

B.1 INTRODUCTION.

All Hewlett-Packard Instrumentation Tape Recorders provide highly flexible yet easy to operate systems to record and reproduce electrical signals on 1/4-inch magnetic tape. The intent in offering the non-IRIG compatible 1/4-inch tape machines is to allow customers not requiring IRIG compatibility a choice of high quality instrumentation recorders at a substantially lower price. These customers who use the same recorder for both data acquisition and reduction have found that they can often buy two or three 1/4-inch recorders for less than one IRIG compatible system. In so doing they not only gain a great deal more flexibility but very often superior performance in their particular application. Future customers should also consider that several thousand of the 3960, 4-channel recorders have already been sold and are regarded by some customers as the 1/4-inch, 4-channel tape standard. The recent introduction of the 3968, 1/4-inch tape 8-channel recorder is another step forward in trying to offer the best price/performance package available to solve the problems of instrumentation tape recording.

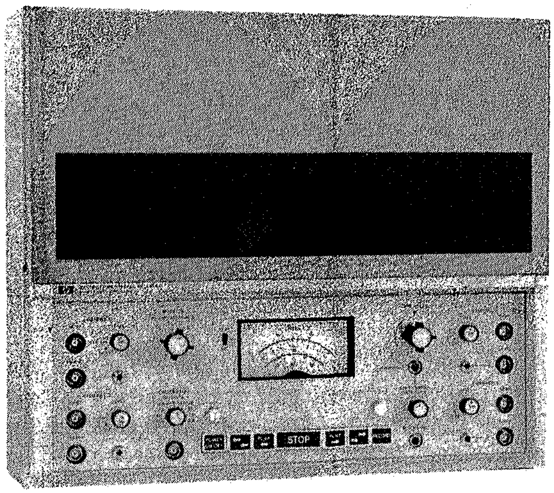
The following pages include a brief description of the 3960 and 3968 system along with the accessories available to further extend these system capabilities.

B.2 PRECISION MILLED ALUMINUM CASTING TRANSPORT BASE PLATE.

Provides mechanical stability of tape motion control components such as heads, guides, and motors, throughout the life of the system. This stability means the performance will not degrade due to warpage, which often happens with aluminum jig plates. Precision, numerically controlled milling means easy replacement of components attached to this casting, such as heads, without precision alignment tools and without shimming.

B.3 NATIONAL AND INTERNATIONAL SERVICE ORGANIZATION.

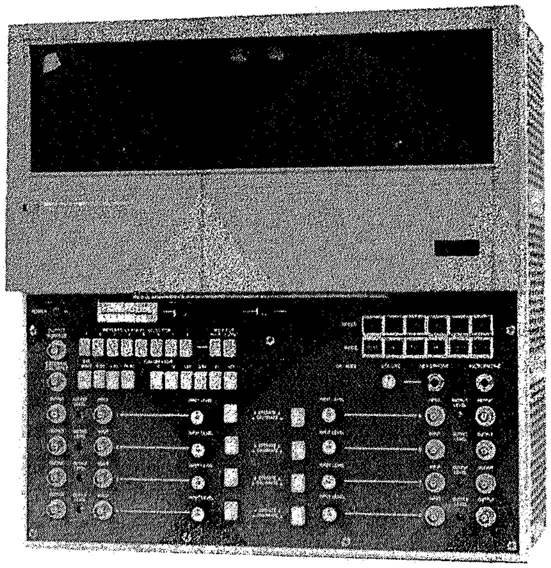
Hewlett-Packard believes that as a manufacturer of measuring instruments it has an obligation to help each user get maximum usefulness from his Hewlett-Packard products. To this end, most Hewlett-Packard field offices have customer service facilities for providing repair and maintenance at a fair price. Local repair facilities are backed up by Regional Repair Centers, located in major industrial areas around the world. A list of HP sales and service offices is included following this section. If you desire more information on any of the products in this appendix, please return the request card which is enclosed.



HP 3960

FEATURES

- TRUE PORTABILITY/ECONOMY in a 1/4-" tape. 4-track, 3-speed, FM/Direct recorder.
- REEL SIZE: standard 5- or 7-inch.
- TIME BASE EXPANSION or contraction by either 16:1 or 10:1. TAPE SPEEDS are: any 3 of octal speeds 15/16 thru 15-ips or decade speeds of 1.5, 3, and 15-ips.
- REFINED OPEN LOOP tape drive with precise crystal reference speed control.
- EXCEPTIONALLY LOW FLUTTER, as exemplified by 44 db (158.1) FM signal-to-noise ratio at 15/16-ips.
- BIDIRECTIONAL record and reproduce.
- PEAK-READING METER.
- BUILT-IN FM CALIBRATION and switchable flutter compensation.
- ELECTRONICS-TO-ELECTRONICS mode.
- OPERATES from most common power sources: 115/230 VAC 48-440 Hz or 12 or 28 VDC.
- HINGED CHASSIS for simplified, quick maintenance.
- NO PERIODIC LUBRATION REQUIRED.
- COMPLETE LINE of accessories available.



HP 3968

FEATURES

- TRUE ECONOMY in a 1/4"-tape. 8-track, 6-speed, FM/Direct recorder.
- REEL SIZE: standard 5- or 7-inch.
- TIME BASE EXPANSION or contraction of up to a 32:1 ratio. TAPE SPEEDS are: 15/32, 15/16, 1-7/8, 3-3/4, 7-1/2, and 15.
- REMOTE CONTROL – All operating and speed selection controls, except power on-off are contact closure and TTL compatible.
- REFINED OPEN LOOP tape drive with precise crystal reference speed control.
- EXCEPTIONALLY LOW FLUTTER, as exemplified by 40 db (100:1) FM signal-to-noise ratio at 15/32-ips.
- BIDIRECTIONAL record and reproduce.
- VOICE CHANNEL for voice annotation on channel 8.
- PEAK-READING METER.
- BUILT-IN DIRECT AND FM CALIBRATION and switchable flutter compensation.
- ELECTRONICS-TO-ELECTRONICS mode.
- OPERATES from most common power sources: 115/230 VAC 48-440 Hz or 12 or 28 VDC.
- HINGED CHASSIS for simplified, quick maintenance.
- NO PERIODIC LUBRATION REQUIRED.
- COMPLETE LINE of accessories available.