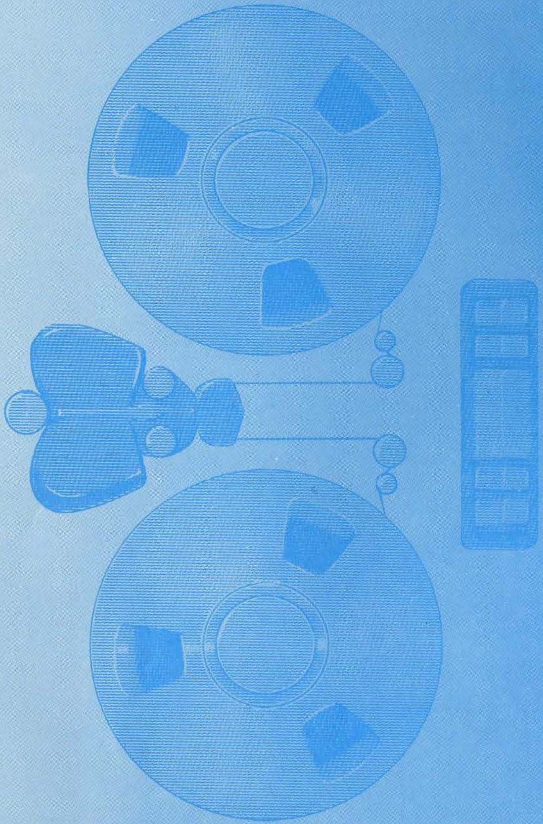
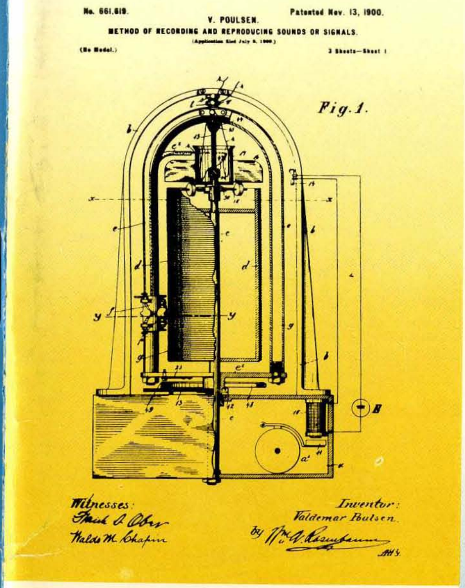




No. 661,619. Patented Nov. 13, 1900.

V. POULSEN.

METHOD OF RECORDING AND REPRODUCING SOUNDS OR SIGNALS.

(Application filed July 8, 1900.)

(No Model.) 3 Sheets—Sheet 1

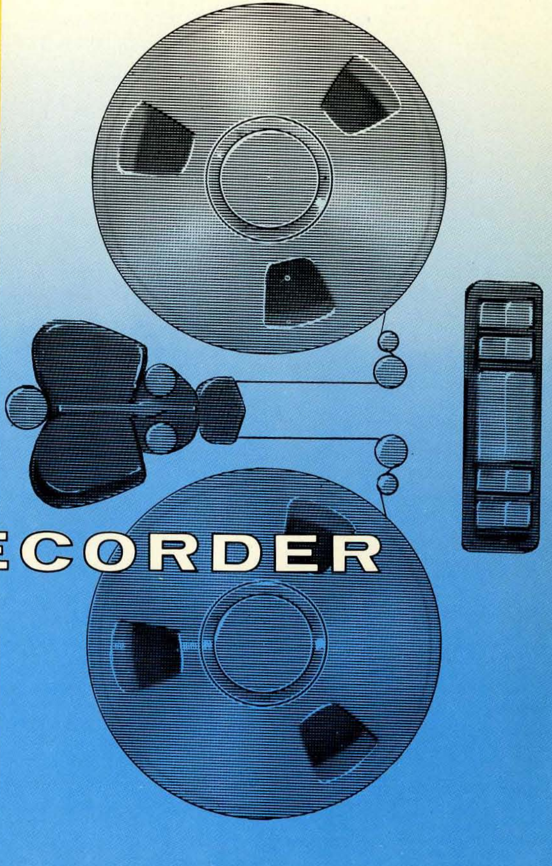
Fig. 1.

Witnesses:
Frank L. Ober
Waldo M. Chapin

Inventor:
Valdemar Poulsen.
by Wm. A. Rosenbaum
Att'y.

PAUL J. WEBER

the TAPE RECORDER *as an instrumentation device*

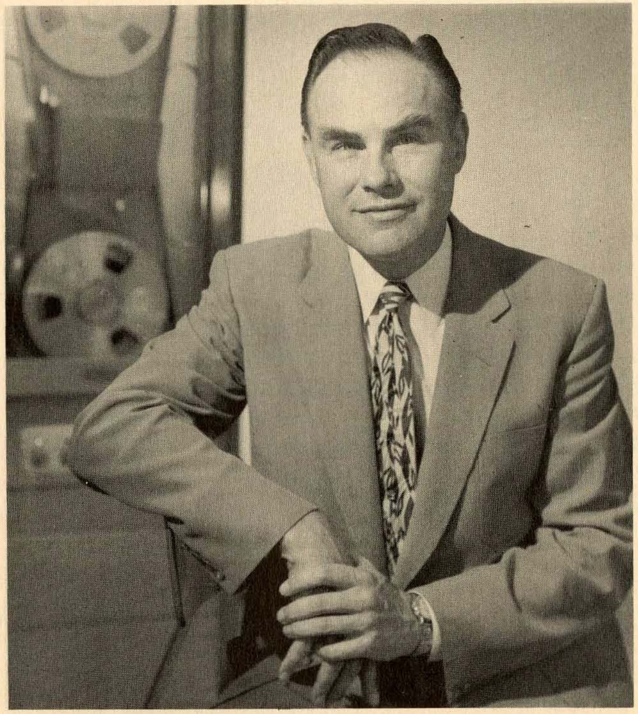


Foreword

The Bureau of Ships has many interests in the field of basic instrumentation; an area which has progressed very rapidly in the last few years is the field of magnetic tape recording. While most are familiar with the impact that the tape recorder has made in the Audio field, it seems very apparent that the tape recorder has a more important place in the overall field of basic instrumentation. The following presentation by Mr. Paul Weber of the Ampex Corporation completely covers the background and present state-of-the-art in this field.

Everett L. Martin

EVERETT L. MARTIN
Department of the Navy
Bureau of Ships (Code 565)
Washington 25, D. C.



The author, Paul J. Weber. After receiving his BSEE degree from Cooper Union Institute of Technology in New York, he attended George Washington University, Washington, D. C., for post-graduate studies. He spent 14 years in charge of the Audio and Acoustics Section of the U.S. Navy Bureau of Ships. Mr. Weber joined Ampex Corporation in 1955; early in 1957 he was promoted from Eastern Regional Sales Manager to Marketing Manager of the Instrumentation Division. His responsibilities include directing sales, service, product planning, market development and advertising activities of the division.

The tape recorder as an instrumentation device

PAUL J. WEBER
Ampex Corporation

From a talk presented to the
Bureau of Ships, Navy Department
Washington, D. C.

Fifteen years ago, a young inventor came to Washington from Chicago to show the Navy's Bureau of Ships a device which he suggested might have possible Naval applications. The man's name was Marvin Camras from the Armour Research Foundation and the device was a Magnetic Wire Recorder. This recorder did not differ greatly from the one conceived and constructed by Sweden's Valdemar Poulsen in 1890—with two significant exceptions. Camras' recorder utilized electron tubes, permitting amplification of the recorded signals; and employed a high-frequency bias signal to overcome the distortions caused by the inherent non-linearities in the magnetic medium.

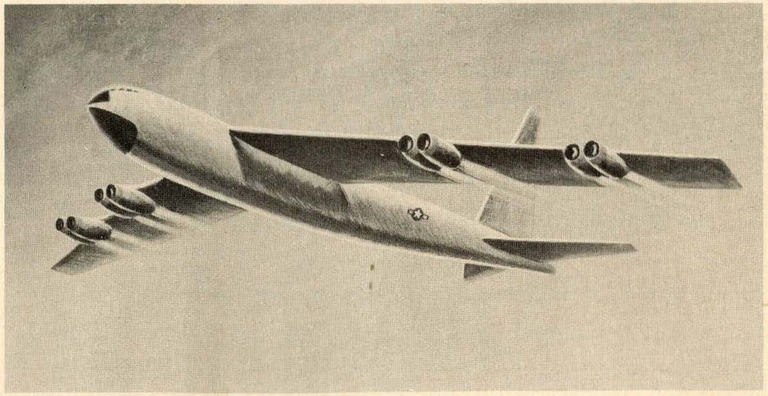
The Navy was quick to recognize the implications of this new recording technique and supported much of the research and development which led first -- to improved wire recorders, and then – to the magnetic tape recorder as we know it today. We are all familiar with the widespread acceptance and usage of magnetic tape recorders for audio purposes – the recording of speech and music for entertainment, training and broadcasting. Even more dramatic in its recent growth and development, although less widely understood and appreciated, have been the advances made in magnetic tape recording for instrumentation purposes. This phase of recording concerns itself with measurement, data storage, data analysis, research and industrial control.

The most exciting thing about the instrumentation recording field is its continuing growth at an ever-expanding rate. There are two principal reasons for the rapid strides being made in applying magnetic recording for instrumentation purposes. First is the need and demand for making very large quantities of measurements at very fast rates; and for reducing this data rapidly to a form which will allow it to be used efficiently and effectively. The other reason centers around the inherent advantages of the magnetic recording process itself. In some cases, it permits the attainment of results which cannot be achieved in any other way.

Let me illustrate the first point:

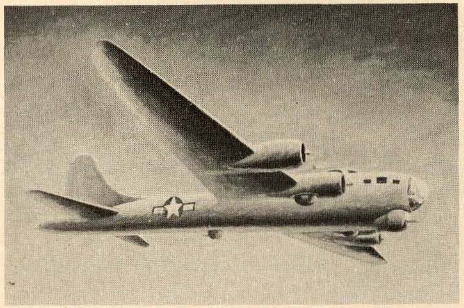
The Need for More Rapid, Efficient and Effective Data Acquisition and Reduction

Consider the problems involved in designing a modern airplane. The flight test is the traditional method used for evaluating the performance of an airplane and gathering the information needed to prove out its basic design. In the early days of flight tests, the pilot would read the instruments on his control panel and note his observations on a pad strapped to his knee. As design techniques were refined, test engineers required more extensive data and introduced more automatic methods of data acquisition to free the pilot for his primary mission of flying the plane. Measurements were brought to dials mounted on a panel which was photographed by a motion-picture camera. Graphic recorders, using pen-and-ink and oscillographic traces on photographic film, permitted continuous recording of high-frequency information, such as vibrations and flutter. Many of these techniques are still in use today and serve a useful purpose. But the demand for more and more measurements and a more rapid reduction of these measurements to usable physical quantities upon completion of the flight, requires the use of more modern techniques. This has been one of the major factors behind the recent growth of magnetic tape development.

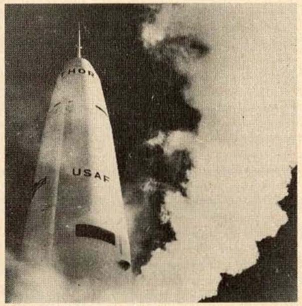


Illust. 2. B-52 bomber.

To illustrate the magnitude of the problem, consider this fact: The number of measurements which have been taken on a single test flight of a B-52 bomber exceeds all of the measurements which were taken in all the flight tests that were ever performed on the old B-17. One jet transport designer today has a test program



Illust. 3. B-17 bomber.



Illust. 4.

which involves taking one million measurements during a single test flight. If these measurements were to be recorded on photo panels, or on oscillographs, several weeks of concentrated effort, involving large numbers of persons, would be required to reduce the data by manual means, before the design engineer would have the significant numbers he needs to either correct or improve the design. In the accelerated plane and missile programs which we face today, time lags of this magnitude cannot be tolerated.

Inherent Capabilities of Magnetic Tape Recording

The second principal reason for the rapid growth of tape for measurement and analysis has been the inherent capabilities of tape itself as a recording medium. Let me briefly catalog some of these advantages which will be amplified later.

The first of these is a very *wide frequency range.* Magnetic tape permits the recording of information from DC up to megacycles.

Second—we have a very *wide dynamic range* of recording, in excess of 50 decibels, permitting accurate and linear recording from full-scale signal level (100%) down to ⅛ of 1% full scale.

Third—magnetic tape has *low inherent distortion* characteristics. When overload occurs, it occurs rather gracefully, as contrasted with a galvanometer or other mechanical devices.

Fourth—the signal information is preserved in its *electrical form*, so that the original event can be recreated at any future time. This lends itself, of course, to automatic reduction of the data when the flight or test is finished.

Fifth—recordings made on tape are available for immediate playback, with no time lost in photographic processing.

Sixth—we have the advantage that the tape itself is *reusable*, since it can be erased. Thus, there are no continuing costs for recording medium, if it is not necessary to preserve the record.

Seventh—tape can be *played back thousands of times*, which permits extracting every bit of useful information from the recording during an analysis.

Eighth — tape provides facility for *multiple-channel recording.* Thousands of channels of information may be recorded simultaneously, using various multiplexing techniques. Very accurate time and phase relationships can be maintained between these simultaneous signal channels.

Finally, tape provides something which no other medium provides —the *ability to alter the time base.* This permits events to be recreated on playback either faster or slower than they actually occurred, with resulting multiplication or division of all frequencies involved.

BASIC ELEMENTS OF A MAGNETIC TAPE RECORDER

My purpose here today is to leave with you an understanding of the magnetic recording process, its advantages, as well as its limitations; to discuss some of the design considerations important to a recorder intended for instrumentation use; and lastly, to review some typical instrumentation applications employing magnetic tape recording. For our purposes, the tape recorder can be considered to be made up of three basic elements, as illustrated in Figure 1.

First there are the *electronic coding devices* which prepare or "encode" the signal information for optimum recording and "decode" it on playback to recover the signal in its original form. The second element is the *magnetic head*, or transducer, which

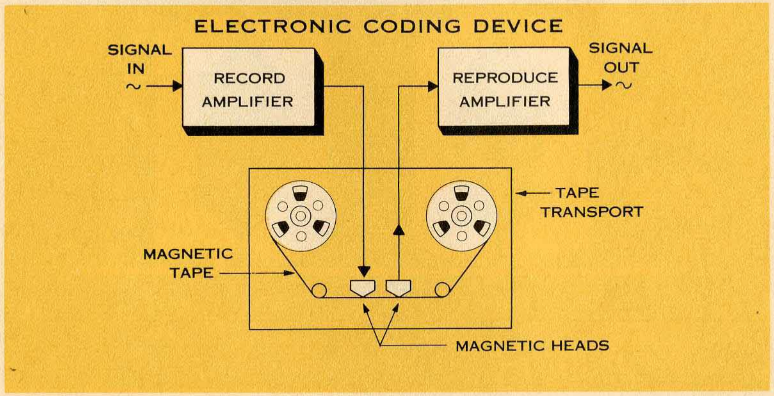


Fig. 1. Basic elements of a magnetic tape recorder.

during the recording process converts the electrical signal into a pattern of varying states of magnetization on the tape medium; and during playback reconverts the varying states of magnetization on the tape into an electrical signal.

The third element is the *tape transport* itself—whose function it is to move the tape medium smoothly across the magnetic heads at a constant linear speed.

I shall discuss each of these elements in turn—starting with the electronic coding devices, usually referred to as Record and Reproduce Amplifiers. There are several distinctly different recording processes in common use—each of which requires a different form of electronic encoding and decoding of the signal information. Four of the more common recording processes will be described and explained.

DIRECT RECORDING PROCESS

The Direct Recording Process is the most familiar, since it is the process used in the recording of speech and music. Here the signal to be recorded is amplified, mixed with a high-frequency bias (whose function will be described later) and presented directly to the recording head as a varying electric current, *i*.

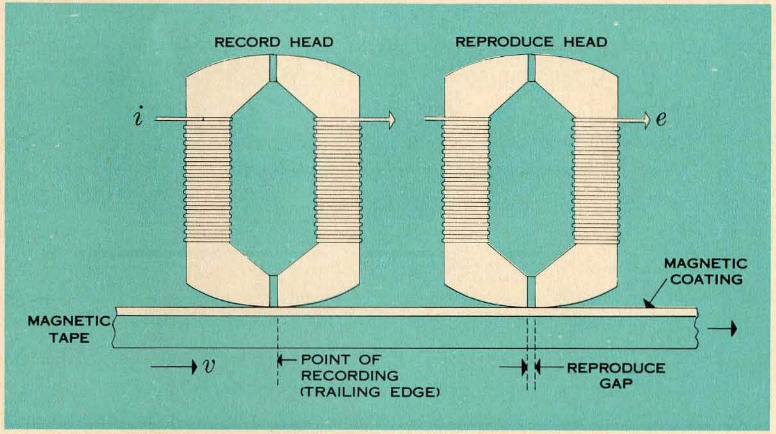


Fig. 2. The magnetic tape recording and reproducing process.

The recording head consists of a magnetic core in the form of a closed ring, having a short non-magnetic gap in series with the magnetic path of the core. This is represented schematically in Figure 2. The magnetic tape consists of a plastic base (such as acetate or Mylar*) on the surface of which fine particles of magnetic material are dispersed uniformly. The magnetic surface of the tape contacts the magnetic head at the gap, in effect shunting the gap and completing the magnetic path in the head core. The signal current flows through a winding which links the magnetic core and produces magnetic flux, ϕ, whose magnitude is proportional to the recording current.

$$\phi = Ki$$

The tape is moving across the heads at a linear velocity of v. Any particle of the magnetic medium crossing the gap remains in a permanent state of magnetization which is proportional to the flux flowing through the head at the instant that particle passes out of the gap. (This proportionality will be discussed further when "bias" is described.) Thus, the actual recording takes place at the trailing edge of the record gap.

If the signal to be recorded is sinusoidal, the intensity of magnetization on the tape will vary sinusoidally along the length of the tape. A wavelength of recorded signal along the tape will occur for each complete alternation of the input electrical signal. This wavelength will be directly proportional to the tape speed and inversely proportional to the frequency of the recorded signal.

$$\lambda = \frac{v}{f}$$

λ = *wavelength on tape (inches)*
v = *tape speed (inches/sec)*
f = *frequency (cycles/sec) of electrical signal*

During playback, the magnetized surface of the tape passes the gap of a reproduce head, which is similar in construction to the record head. The portion of tape in contact with the gap is bridged by the magnetic core of the reproduce head, which causes magnetic lines of flux to flow through the core. The magnitude of this flux is a function of the average state of magnetization on that portion of the tape actually spanned by the gap at any given

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* Du Pont trademark

instant. As the tape passes by the reproduce gap, the amount of flux through the core varies with the varying state of magnetization on the tape and causes a voltage to be generated in the winding linking the core. It is important to note that the voltage generated is proportional not to the magnitude of the flux—but to its *rate of change.*

Thus, if flux is proportional to the recording current,

$$\phi = Ki = K \sin (2\pi ft)$$

the playback voltage from the reproduce head is

$$e = K' \frac{d\phi}{dt} = K'' \frac{d}{dt} \sin (2\pi ft)$$
$$= 2\pi K'' \times f \times \cos (2\pi ft)$$

From this, we can see that the playback voltage is dependent upon the frequency and for constant-current recording (recording current constant at all frequencies) the output voltage will vary in direct proportion to frequency.

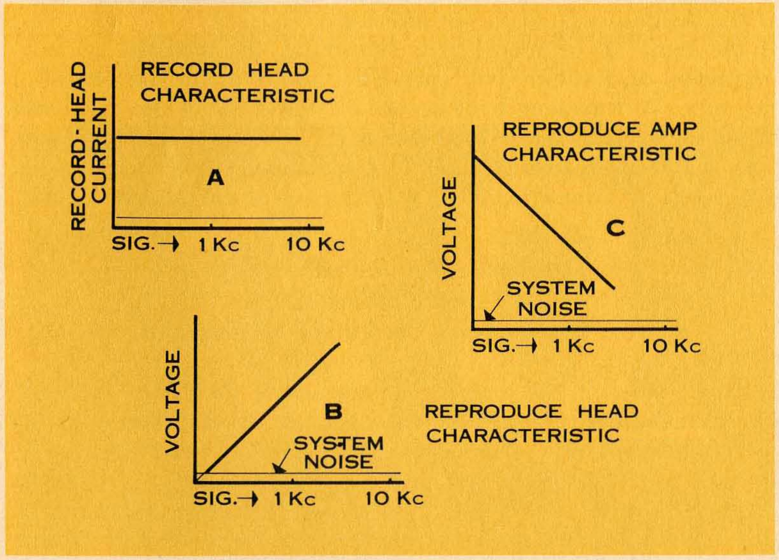


Fig. 3. Effect of frequency on recording and reproducing characteristics.

Figure 3 illustrates the effect of frequency on the recording and reproduce characteristics and calls attention to two facts. The first is that our reproduce (decoding) amplifier must have a frequency response characteristic which is the inverse of the reproduce head characteristic, in order that an overall flat frequency response can be obtained. This is referred to as "playback equalization" and is illustrated in Figure 4.

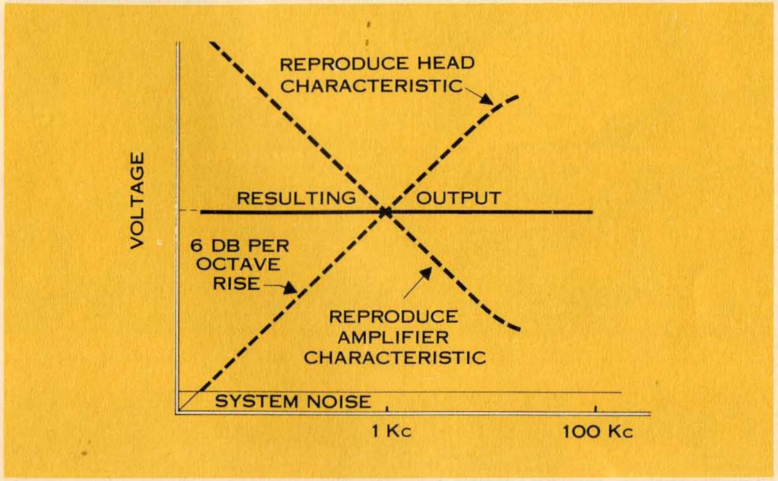


Fig. 4. Reproduce amplifier output.

The second fact we observe is that as we go lower and lower in frequency, the output voltage from the reproduce head decreases until it approaches the inherent noise level of the system. At this point, it is impossible to recover the signal by equalization. This condition leads us to the first and principal limitation of the Direct Recording Process: there is a *lower frequency limit,* below which it is impossible to record and playback successfully.

Gap Effect

Let us now explore the high-frequency end of the recording spectrum. We will discover a limitation here which is fundamental to all recording processes. Figure 5A illustrates the reproduction of a relatively long wave length of recorded signal on the tape.

As mentioned before, the average value of tape magnetization spanned by the gap is continually changing, resulting in an output voltage from the head.

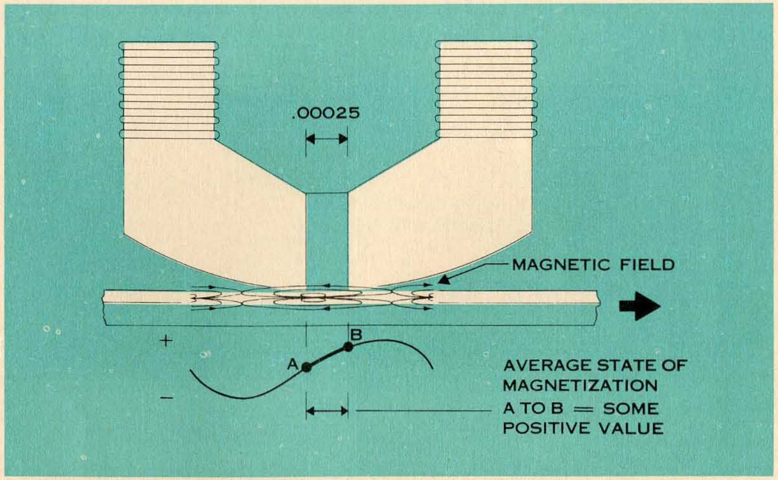


Fig. 5a. Gap effect at low frequency.

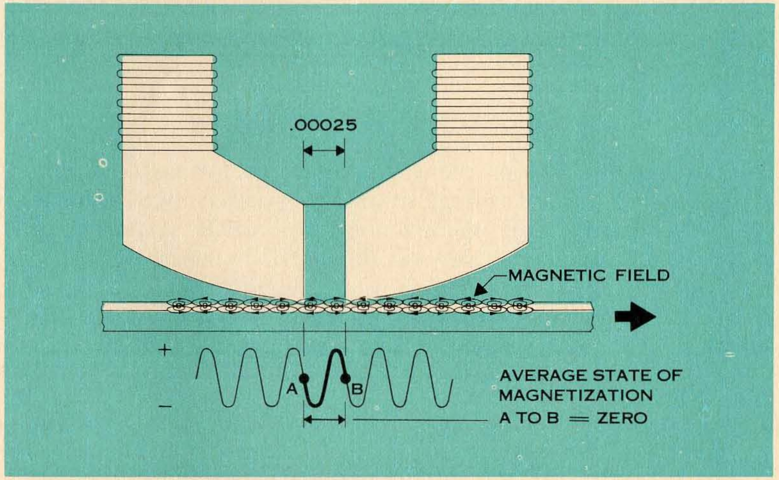


Fig. 5b. Gap effect at high frequency.

In Figure 5B, we have a much shorter wave length, equal in length to the dimension of the gap itself. Under this condition, the average magnetization in the gap is zero and does not change as the tape moves by. The output from the head is therefore zero, and is represented by point *A* in Figure 6. And as the frequency approaches that value at which the wave length equals the gap width, the output from the reproduce head falls off rapidly.

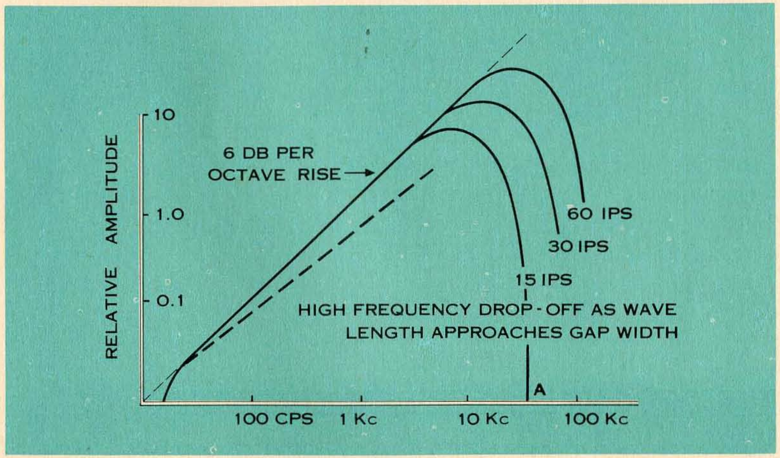


Fig. 6. Reproduce head output.

Although the limitation on high-frequency response resulting from this "gap effect" cannot be eliminated, it can be improved in two ways:

$$\textit{since } e \to o \textit{ as } \lambda \to d, \textit{ and } \lambda = \frac{v}{f}.$$

We can record and playback higher frequencies by either reducing the size of the reproduce gap, or by increasing the tape speed. Either of these two alternatives, however, involves a compromise in some other desirable characteristic. If we reduce the gap size in an effort to get better resolution of high frequencies, the voltage output from the reproduce head will fall, as shown by the dotted curve in Figure 6. The result will be a deterioration in dynamic range or signal-to-noise ratio.

If, on the other hand, the tape speed is increased, head wear will be correspondingly increased and head life reduced. The three factors which are interrelated are shown in the pie-chart of Figure 7.

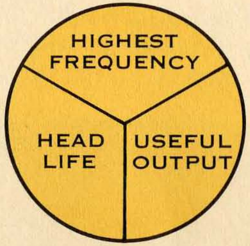


Fig. 7. Relation of head-design parameters.

Optimum head design requires striking the best balance between these mutually conflicting parameters. You may be interested in knowing the actual numerical values of those parameters which are in common use today.

Tape Speed: 60 inches/second.

Gap Width: 0.00025 inches.

Frequency Response: 100,000 cycles/second at 60 inches/second or 1600 sine-wave cycles/inch of tape. This latter number can be taken as a figure of merit for the Direct Recording System and can be used as a basis of comparison with other recording systems.

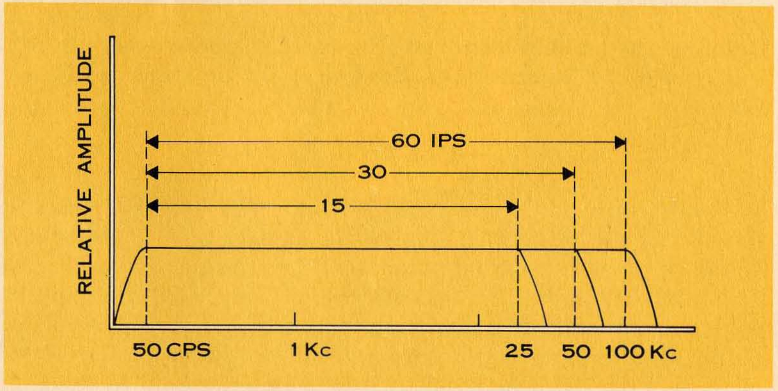


Fig. 8. Direct-record frequency response.

Dynamic Range (signal-to-noise ratio): The dynamic range is the ratio of the maximum signal which can be recorded (at a given level of distortion) to the minimum signal which can be recorded (determined by the inherent noise level of the system). As the recording level is increased into the nonlinear magnetic characteristic approaching saturation, the distortion increases correspondingly. The bar graph in Figure 9 illustrates some typical values for dynamic range expressed in decibels.

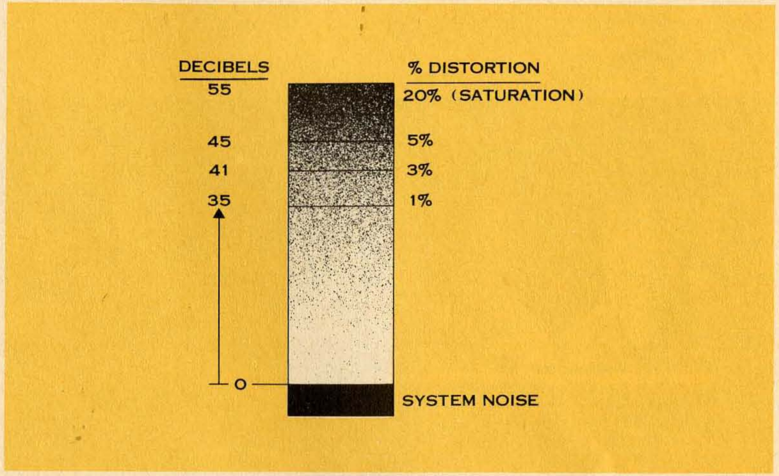


Fig. 9. Dynamic range.

Amplitude Instability

The second major limitation of the Direct Recording Process is one referred to as *amplitude instability.* This is a condition brought about by causes external to the recorder itself, namely, the surface condition of the magnetic tape medium. The effect manifests itself by instantaneous lapses or reduction in signal level, which are commonly referred to as "drop-outs."

Magnetic tape is manufactured in such a way that the magnetic (iron-oxide) particles are ground to a very small size and applied to the surface of the tape in as uniform a coating as possible. In spite of all reasonable precautions, the surface of the tape does not end up entirely smooth and homogeneous. Surface defects of various types occur. The most serious of these are "nodules" or clusters of oxide particles which form along the surface of the tape. As these nodules pass across the head, they cause the tape to be lifted away from the head and result in a drop in signal level. A similar drop in signal level will occur if a foreign particle of dust or dirt is permitted to find its way onto the surface of an otherwise perfect tape.

The effect is most serious at the shorter recorded wave lengths (high-frequency signals), ones which approach the size of the nodules or foreign particles. Figure 10 illustrates the magnitude of this effect.

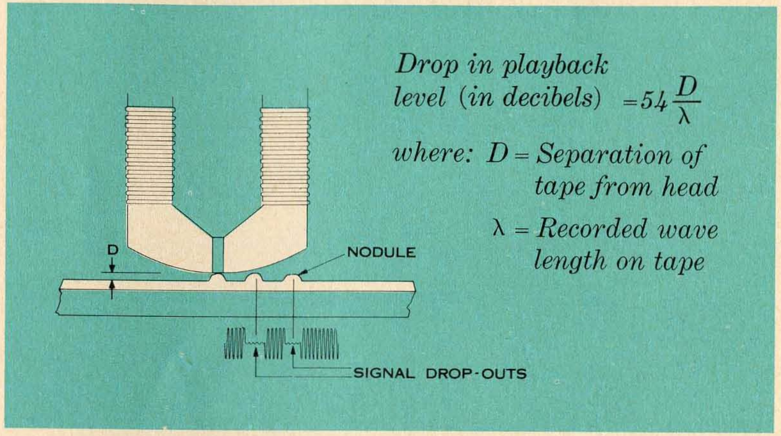


Fig. 10. Effect of tape-surface imperfections.

The "drop out" effect is relatively unimportant for audio recording, because the ear tends to integrate variations in signal level which occur instantaneously and, thus, is insensitive to them. For instrumentation recording, on the other hand, this effect might be intolerable, as for example if it is required to preserve accurately the waveshape of a transient phenomenon.

High Frequency Bias

In introducing the Direct Recording Process, I mentioned that the signal to be recorded was mixed with a *high-frequency bias.* Let me now explain the role which the "bias" plays. Magnetic materials are all characterized by the nonlinear relations between the magnetic force applied to them and their resulting state of magnetization. This, in itself, would seem to disqualify them for use in a "low distortion" recording system.

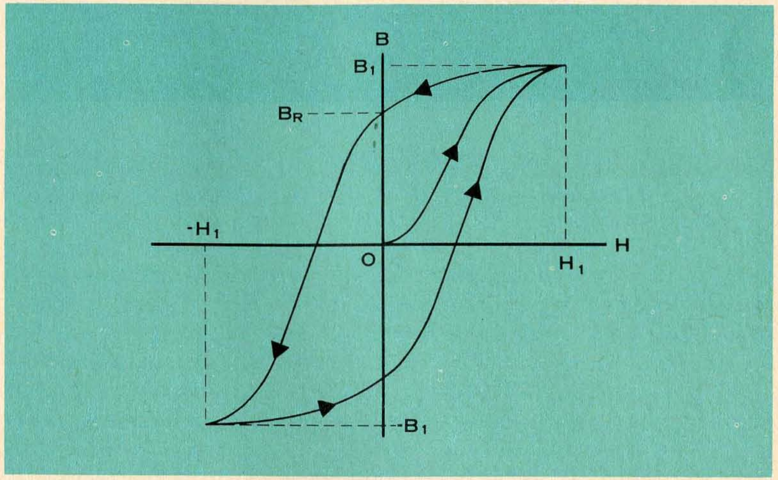


Fig. 11. Typical magnetization curve.

Figure 11 shows the typical relation existing between the magnetizing force H applied to the portion of the tape under the recording head gap and the resulting magnetization B starting at O with a demagnetized tape. The magnetizing force H is proportional to the product of the number of turns on the recording head winding and the recording current through the winding. If this value of magnetizing force is H_1 at the instant a given portion of tape is about to pass out of the recording gap, its magnetization will be B_1 while still in the gap, and will drop to B_R as it leaves the gap. B_R represents the remanent magnetization on the tape after the magnetizing field has been removed (or the portion of tape has left the magnetic field in the gap).

If we were to plot the values of remanent magnetization B_R corresponding to various values of magnetizing force H, we would have a curve which represents the actual recording characteristic of the magnetic medium, as illustrated in Figure 12A.

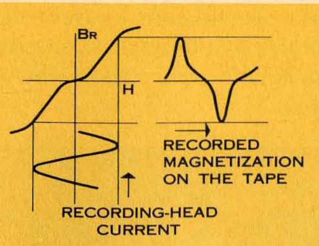


Fig. 12a. Recording characteristic of the magnetic medium.

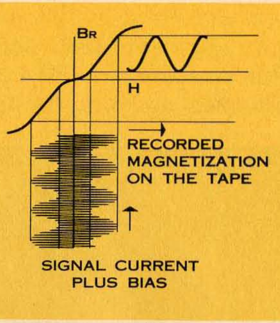


Fig. 12b. Addition of high-frequency bias to the recording signal.

Here the inherent nonlinearity of the recording process becomes apparent. We observe, however, that the characteristic is essentially linear over a portion of its total range—that portion above the toe of the curve (corresponding to low values of magnetization) and below the knee of the curve (corresponding to high values of magnetization approaching saturation). If a high-frequency bias is mixed with the signal to be recorded, it is possible to present to the recorded signal only the straight-line portion of the recording characteristic. This effect is illustrated in a simplified manner in Figure 12B.

The amplitude of the bias signal is several times that of the recorded signal. It is important to note that the combining of the bias and recorded signal is accomplished by a linear mixing process, with no new sum and difference frequencies being introduced. This mixing is not an amplitude-modulation process, in which new frequencies would be generated. This distinction is further illustrated in Figure 13.

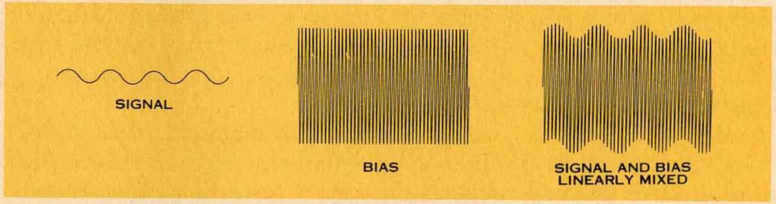


Fig. 13. Mixture of bias and signal.

The bias frequency does not otherwise enter into the recording process, or the subsequent playback process. The wave lengths, which would correspond to the high-frequency bias signal, would be too small to be resolved by the playback head. The actual value of the bias frequency is not too critical. It is usually selected to be at least 3.5 times the highest frequency to be recorded, to minimize any interaction which might occur between the bias frequency and higher-order harmonics of the recorded signal frequencies.

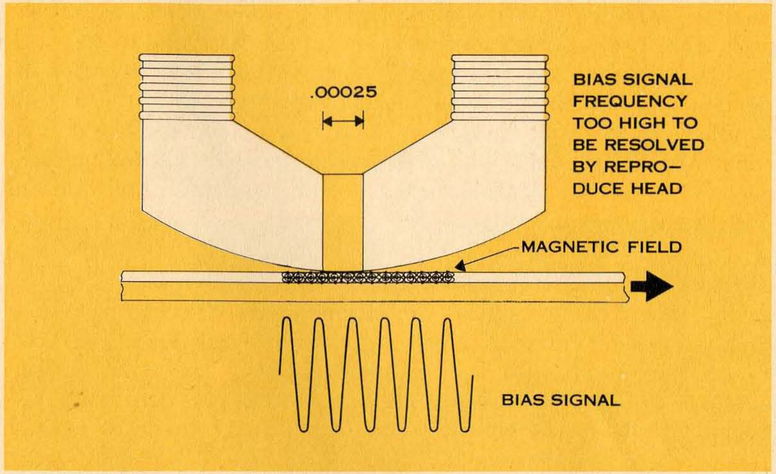


Fig. 14: Relationship of bias signal to reproduce head.

Audio Recorders

Before leaving the Direct Recording Process, it would be well to mention the inherent dangers of using an audio recorder for instrumentation purposes. An audio recorder may be considered to be a special case of the Direct Recording Process. The characteristics of the record and reproduce amplifiers are modified to conform to the particular characteristics of speech- and music-type signals. It has been established that the energy content in speech and music signals is not uniformly distributed over the range of signal frequencies. For this reason, pre-equalization circuits are incorporated in the record amplifier which pre-emphasize some portions of the frequency spectrum (the extreme low and high ends). These are the frequencies at which the energy content of audio signals is low. By raising their level, it is possible to approach a constant-flux recording situation on the tape at all frequencies. In this way, we can achieve benefits in signal-to-noise ratio without sacrifice in distortion. Of course, the inverse frequency-response characteristic must be introduced in the reproduce amplifier, in the form of post-equalization, to counteract the effect of the pre-equalization and produce a final output signal which is a replica of the original input signal.

The danger in using an audio recorder for instrumentation recording is that the instrumentation-type signal does not in general have the peculiar spectral energy distribution characteristics of speech or music. The result is that the pre-emphasis in the record amplifier could result in serious distortion of the high and low frequencies. This could only be overcome by reducing the recording level by a considerable amount—with resulting deterioration of the signal-to-noise ratio of the recording.

Applications of Direct-Record Process

Having stated the two major limitations of the Direct Recording Process, let me mention its advantages. The Direct Recording Process is the one having the widest frequency spectrum. Using practical tape speeds, signals can be recorded over a continuous range of frequencies from 50 cps to 100,000 cps. Other advantages are its wide dynamic range and its ability to handle moderate overloads gracefully, without sudden or drastic increases in distortion. The major applications for the Direct-Record process are:

1. The recording of signals where the significant information is contained in the relation between frequency and amplitude on a logarithmic basis. Examples are in the measurement and subsequent spectrum analysis of noise and underwater-sound signals.
2. The recording of voice commentary on one of the tracks of a multitrack recorder for the purpose of logging and identification.
3. Multiplexing a number of signals simultaneously on one track by assigning to each channel of signal information a separate portion of the wide frequency spectrum which is available in the Direct Recording Process. This application will be described more fully in the next section.

FREQUENCY MODULATION RECORDING PROCESS

There is a way to overcome the two basic limitations of the Direct Recording Process, which are the inability to record very low frequencies and the amplitude instability caused by tape drop-outs. This method employs a carrier frequency which is frequency-modulated by the signal to be recorded. Thus, a particular frequency is selected as the center frequency corresponding to zero input signal. A DC signal of positive polarity would deviate the carrier frequency a given percentage in one direction. A DC signal of negative polarity would deviate the carrier frequency an equal percentage in the opposite direction. An AC input signal would deviate the carrier alternately on both sides of center frequency, at a rate equal to the frequency of the input signal. Thus, all information presented to the tape is preserved in the frequency domain and normal amplitude instabilities will have little or no effect on the recording.

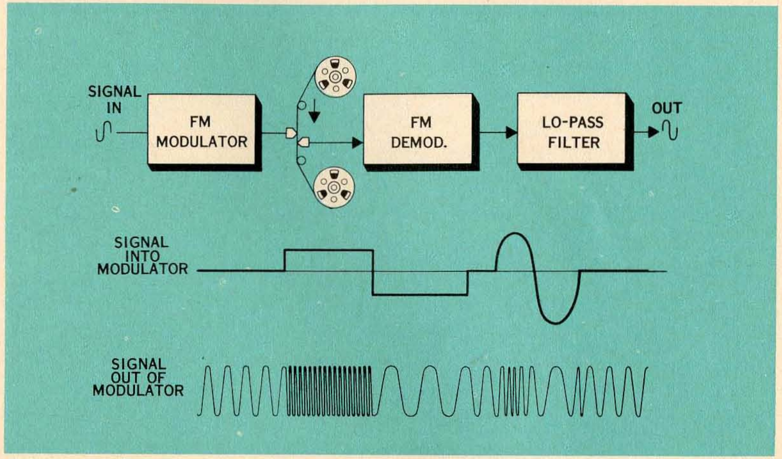


Fig. 15. Basic FM system.

Figure 15 illustrates an elementary block diagram of the electronic coding employed in the Frequency Modulation Recording Process and illustrates the relation between the input signal and the signal presented to the recording head. On playback, the signal is demodulated and fed through a low-pass filter which removes the carrier and other unwanted frequencies generated in the modulation process.

The first widespread application of the FM recording technique was in *frequency-division multiplexing* where a number of individual carrier frequencies (F_1, F_2, F_3 . . .) are each modulated by a separate input signal (f_1, f_2, f_3 . . .) as illustrated in Figure 16.

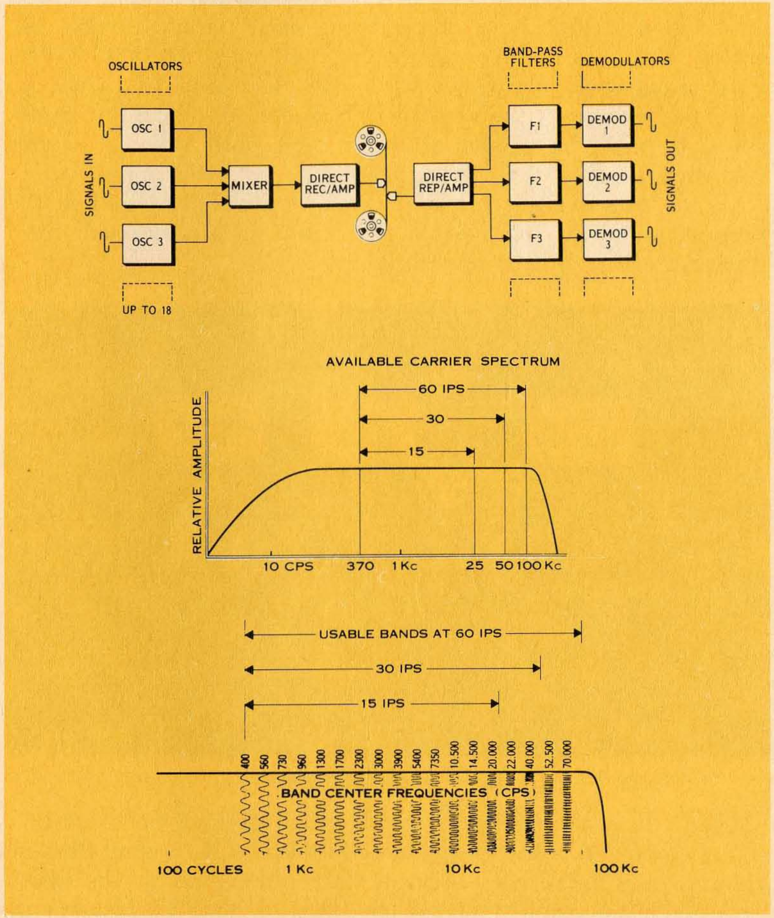


Fig. 16. Basic frequency-multiplexing narrow-deviation FM system.

The resulting multiplicity of signals is then mixed linearly and the composite signal recorded using the Direct Recording Process. Thus, the wide bandwidth and the linearity of the Direct Recording Process is used to permit the simultaneous recording of many channels of signal information on one track of tape.

It is important to note that the FM recording process makes very stringent demands on the ability of the tape transport to move tape across the heads at a precisely uniform speed. Any speed variations introduced into the tape at its point of contact with the heads will cause an unwanted modulation of the carrier frequency and result in system noise. This is the limiting factor in the dynamic range and accuracy of the FM system.

This limitation, caused by speed variations (flutter and wow), is particularly acute in the frequency-multiplex scheme just described. In order to record a multiplicity of carriers in the available frequency spectrum, it is necessary to restrict the maximum frequency deviation of any one carrier. The frequency deviation commonly used has been ± 7.5% of center frequency. Thus, if a 7.5% frequency deviation corresponds to a 100% input signal, a 1% deviation in frequency resulting from flutter or wow in the transport would appear as a

$$\frac{100}{7.5} = 13.3\% \text{ noise signal.}$$

We see then that any speed variation in the transport would be multiplied by a factor of 13.3.

Where it is desired to use the FM recording process over a wider total signal-frequency range, with a wider dynamic range and greater overall accuracy, a *wide-deviation FM system* can be used. Here only one channel of signal is recorded on a track of tape and the entire frequency bandwidth of the recorder is used for this signal, as shown in Figure 17. It is possible to design modulators which will permit deviations of ±40% of center frequency without sacrifice of linearity. In this case, a 1% tape-speed error would only cause a

$$\frac{100}{40} = 2.5\% \text{ noise signal,}$$

giving an improvement of better than five times that of the narrow-deviation system first mentioned.

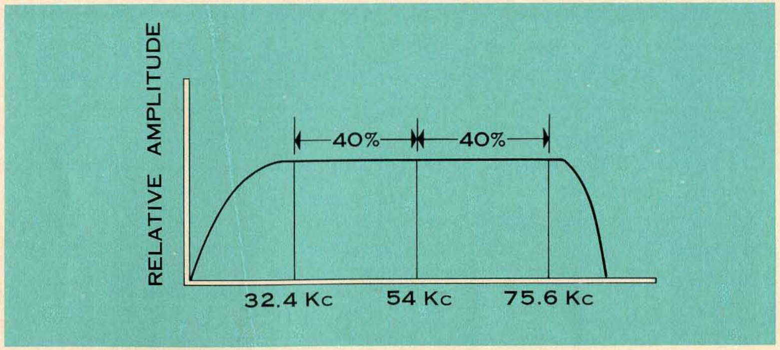


Fig. 17. Wide-deviation FM-carrier bandwidth.

Actual values for the frequencies employed at a 60-ips tape speed are:

Input Signal	*Modulator Frequency* (at 60 ips)	*Deviation*
+ 1.4 volts DC	75.6 Kc	+ 40%
0	54 Kc	Center Frequency
− 1.4 volts DC	32.4 Kc	− 40%

Referring back to the block diagram in Figure 15, the low-pass filter following the demodulator would have a cut-off frequency approximately one-fifth that of the carrier frequency—permitting the recording of signals from DC to 10 Kc at a 60-ips tape speed. This then gives a figure of merit for the Frequency Modulation Recording Process of 167 sine-wave cycles per inch of tape (which can be compared with the 1600 cycles per inch of the Direct Recording Process).

If it is not required to record frequencies as high as 10 Kc, the tape speed can be reduced in direct proportion to the desired upper-frequency limit, with proportional increase in recording time. When this is done, the center frequency is scaled down in direct proportion to the tape speed, using the same ± 40% deviation. Thus, the wavelength recorded on the tape corresponding to a given DC signal voltage is the same, independent of tape speed. This makes it possible to record at one tape speed and reproduce at an entirely different tape speed, permitting time base changes—one of the important applications of the FM recording process.

Applications of the Frequency Modulation Process

The *advantages* of the Frequency Modulation Recording Process are: (1) its ability to record low frequencies down to DC; (2) its freedom from the effects of tape drop-outs; and (3) its excellent phase-shift versus frequency characteristics with the attendant ability of accurately preserving the waveform of a recorded signal. The *disadvantages* of the FM process – or the "price" we pay for the advantages are: (1) less efficient utilization of the tape, requiring approximately ten times the tape speed for a given upper-frequency limit; (2) the additional complexity of the electronic circuitry requiring modulators, demodulators, and low-pass filters; and (3) the requirement for a tape transport which is engineered and manufactured to high standards of precision.

The major applications for the FM Recording Process are:

1. The recording of low-frequency signal information, such as vibrations, noises, and under-water sounds for spectrum analysis.
2. The recording of transient phenomena, such as shock, blast and ignition, where accuracy of wave shape is important. Short transients having rise times as short as 125 microseconds can be resolved with this process.
3. Changes in time base permitting a speed-up or slow-down of a given event; and permitting the frequency components of a given signal to be scaled up or down by large factors, up to 1000 times or more.

PULSE DURATION MODULATION RECORDING PROCESS

We have discussed a frequency-division multiplexing technique for recording a number of signal channels on a single recorder track by sharing the available frequency spectrum among the signal channels. There is a second technique to accomplish a similar result, in which *time* can be shared between a number of channels of signal information. This technique is called *time-division multiplexing* and requires an instantaneous sampling of a number of signal channels on a sequential basis.

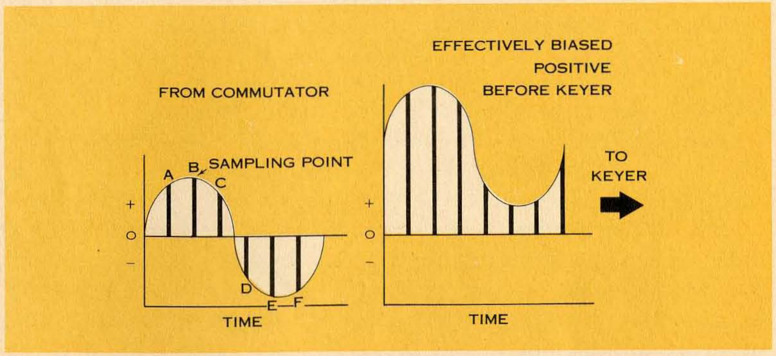


Fig. 18. Sampling a signal in PDM.

When we wish to record the sine wave in Figure 18, we normally think of a continuous recording of each instantaneous value of the wave. It is possible, however, to sample the sine wave at uniformly spaced discrete intervals; record only the instantaneous values at the time of sampling; and then reconstruct the original sine wave on playback by passing the discontinuous readings through an appropriate filter. An accurate reproduction of a sine wave can be made using as few as six samples per sine-wave cycle shown as points A through F in Figure 18. This technique is, of course, equally valid for non-sinusoidal signals, provided the sampling rate is at least six times the highest significant frequency component of the non-sinusoidal wave.

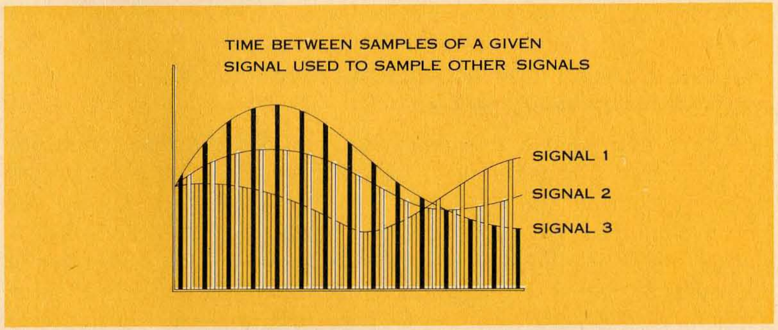


Fig. 19. PDM sampling technique.

If a data signal is being sampled at discrete intervals, it is possible to use the time between these sampling intervals for the purpose of sampling other data signals. This is most conveniently accomplished using a rotating commutator, as shown in Figure 20A, wherein the outputs of a number of transducers are being sampled in sequence, once per revolution of the commutator. Figure 20A is a simplified block diagram of the entire PDM recording system and should be referred to throughout the following discussion.

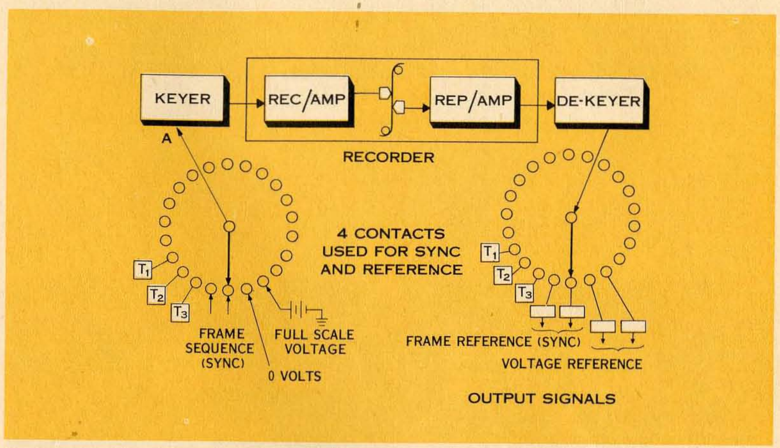


Fig. 20a. PDM recording.

Two of the contacts on the commutator are usually reserved for frame reference to allow synchronization with the commutator used on playback. Two of the other contacts can be used for calibration signals, one corresponding to full-scale voltage, and the other corresponding to zero voltage. Thus, the system permits continuous calibration (once each revolution of the commutator). The remaining sets of contacts are available for connection to the outputs of various transducers (T_1, T_2, T_3 . . .).

The standard system established by the Research and Development Board for telemetry purposes is based on the use of 900 samples per second. This permits some flexibility in system design, where we can employ a 30-contact commutator rotating at 30 revolutions per second; or a 45-contact commutator rotating at 20 rps; or a 90-contact commutator rotating at 10 rps. Using the first of these combinations, we can record 26 channels of information (subtracting the 4 contacts used for frame reference and calibration) each having an upper-frequency limit of 5 cps (30 revolutions or samples per second, where 6 samples determine a sine-wave cycle). By using other combinations, we can record more channels having a lower frequency content, or vice versa. The following table shows some of these possible combinations.

Possible Combinations using a 900 Sample/Second System

Commutator		*Signal Information*	
No. of Contacts	*RPS*	*No. of Channels*	*Upper Freq. Limit*
30	30	26	5
45	20	41	3
90	10	86	1.5

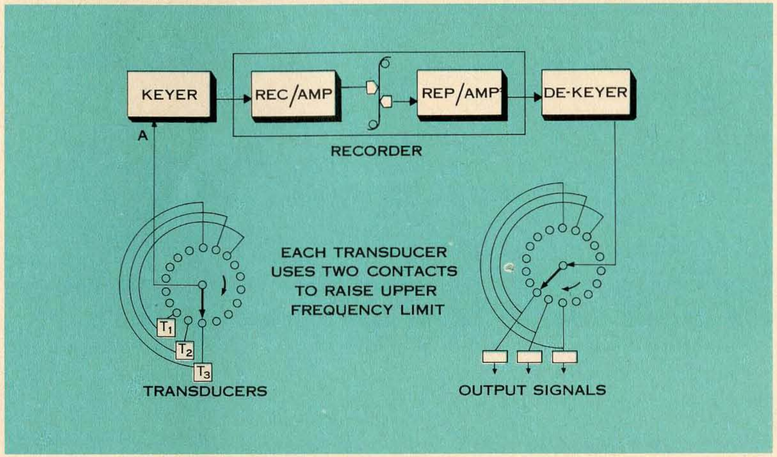


Fig. 20b. PDM recording.

Additional flexibility is possible by paralleling 2 or more contacts and connecting them to the same transducer. This will increase the number of samples per second (and consequently the upper frequency limit) at the expense of fewer data channels, where the

higher frequency response is needed for only a few of the channels. Let us now examine the signal out of the commutator (point *A* in Figure 20A). We have a sequence of very-short-duration pulses of varying amplitude occurring at intervals of once every 1100 microseconds (the reciprocal of 900 samples per second). These appear as shown in Figure 21A).

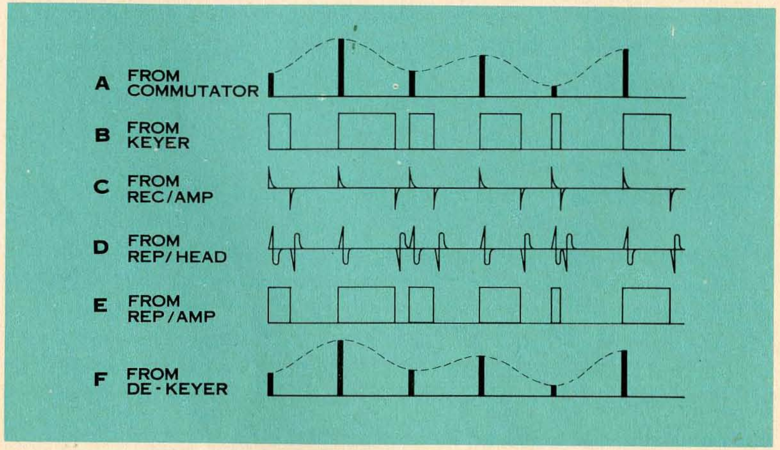


Fig. 21. Signals at various points in PDM.

For the reasons discussed in the Direct Recording Process, the inherent amplitude instability of magnetic tape would prevent accurate and dependable recording of these varying-amplitude signals. So, the signals are passed through a "keyer" which converts them from varying-amplitude signals into constant-amplitude signals of varying pulse-width or pulse-duration, as shown in Figure 21B. A definite pulse width can be assigned to each value of input signal amplitude within the 1100 microsecond total interval available between samples. The following pulse durations are normally used:

Input Signal Voltage	*Pulse Duration*
0	90 microseconds
5 volts (full-scale)	660 microseconds

Any intermediate voltage between zero and full-scale would be represented by a definite pulse duration somewhere between these two limiting values.

Since the only significant information in the signals from the keyer *B* is contained in the time at which each pulse begins and ends, the record amplifier (encoder) sharply differentiates these pulses, presenting to the record head a positive "spike" corresponding to the beginning of a pulse and a negative "spike" corresponds to the end of a pulse. This is shown in Figure 21C. Here, too, it is important to use a tape transport having a minimum of instantaneous tape-speed variation. But flutter and wow is less critical in this process because only the integrated speed errors occurring between the instant of pulse-start and pulse-stop would introduce an error in the recorded data.

The output from the reproduce head consists of a differentiation of the recorded "spike," since, as was explained before, the reproduce head responds to rate-of-change of magnetization on the tape. The wave form out of the reproduce head is shown in Figure 21D, where the point of axis crossing of the reproduced wave represents the instants of pulse-start and stop. The reproduce amplifier (decoder) contains a multivibrator which recreates the original pulses from the output of the reproduce head, resulting in the signal in Figure 21E, which is a replica of Figure 21B, the original varying-width pulse.

These pulses are then fed through a "de-keyer," where they are converted back into varying-amplitude pulses of short duration, as shown in Figure 21F, which in turn is a replica of the original output of the commutator—Figure 21A. The final operation is to feed this output into another commutator where decommutation occurs and the original data channels are separated out into their individual filters. These filters serve to reconstruct and deliver the original data signals.

Applications of Pulse Duration Modulation Recording Process

The chief *advantage* of the Pulse-Duration Modulation Recording Process is its ability to record a large number of simultaneous channels of information. Using a 10 rps by 90-contact commutator, it is possible to record 86 channels of information on one track of tape, or 1200 channels of information on a 14-track recorder. Other advantages are the high accuracy (better than 1% overall) made possible by the self-calibrating feature; and the inherently high signal-to-noise ratio, resulting from the narrow signal-frequency bandwidths involved.

The *disadvantage* of the PDM process is the limited frequency response of each channel; the less efficient utilization of the tape (one-quarter that of the FM process—giving a comparative figure of merit of 40 sine-wave cycles per inch of tape); and the increased complexity of the auxiliary electronic equipment, such as commutators, keying amplifiers and filters.

The *applications* of the PDM recording process are all those which involve a multiplicity of signal channels having relatively low-frequency content. Examples are flight testing and engine testing, where the information to be recorded is derived from a large number of transducers, such as thermocouples and strain gauges.

DIGITAL RECORDING PROCESS

A fourth technique of recording is the Digital Recording Process, which has been growing rapidly in importance as a result of the widespread application of digital computers to electronic data processing systems. As in the PDM system, a sampling technique is used to measure a varying signal. The sampled readings are then converted into a code consisting of a series or group of binary digits. In contrast with the familiar decimal system which employs ten digits (0 through 9), the binary system employs only two digits (0 and 1); and all numbers are expressed in terms of these two digits.

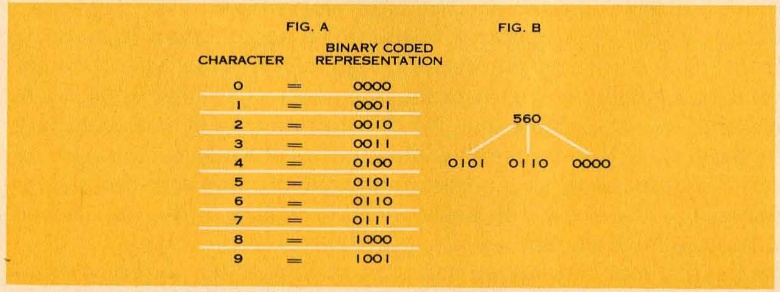


FIG. A

CHARACTER		BINARY CODED REPRESENTATION
0	=	0000
1	=	0001
2	=	0010
3	=	0011
4	=	0100
5	=	0101
6	=	0110
7	=	0111
8	=	1000
9	=	1001

FIG. B

Fig. 22. Binary-coded decimal system.

Digital recording is accomplished by magnetizing the tape to saturation in either of its two possible directions (+ or −) at discrete points along its length. Thus, there is only one of two states of magnetization at any point on the recorded tape; namely, saturation in one direction (+) or saturation in the opposite direction (−). Either of two techniques are commonly employed for recording binary digits:

A. *Return-to-Zero* (RZ). In the return-to-zero method of digital recording, one state of saturation (+) would be assigned to the digit (1) and the opposite state of magnetization (−) would be assigned to the digit (0). Thus, the digital number 010101010 would be recorded as shown in Figure 23A.

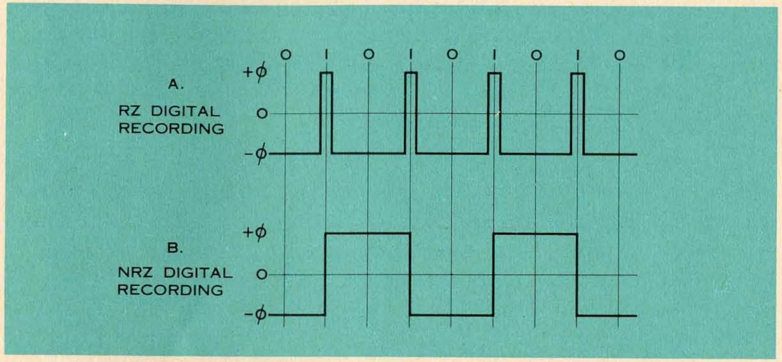


Fig. 23. Digital recording systems.

B. *Non-Return-to-Zero* (NRZ). In the non-return-to-zero method of digital recording, no fixed state of magnetization is assigned to either (1) or (0). Rather, the state of magnetization is reversed from whatever it is each time the digit (1) is to be recorded, and remains unchanged for recording the digit (0). This is shown in Figure 23B. It is seen that NRZ is the more efficient recording method, since it permits twice the number of digits to be recorded for the same number of pulses (reversals of magnetization). This makes possible twice the pulse-packing density on the tape when using the NRZ method.

In the decimal system, we can express any of ten different numbers (0 through 9) using one digit. Using two digits, we can express 100 different numbers (0 through 99). Using *n* digits, we can express 10^n different numbers. Similarly, in the digital system, we can express two numbers (0 and 1) using a single digit; four possible numbers using two digits; and 2^n possible numbers using *n* digits. Thus, we see that the accuracy with which a given number can be stated in digital nomenclature is limited only by the number of digits you wish to use. For example:

No. of Digits	*Possible Accuracy*
5	1 part in 2^5 (or 32) 3%
7	1 part in 2^7 (or 128) 1%
10	1 part in 2^{10} (or 1024) 0.1%

This is one of the major advantages of the Digital Recording Process—it places no arbitrary limit on the accuracy of the system. We are not concerned with the dynamic range of the tape, its linearity, or the type of signal-to-noise problems encountered in the other recording processes. Here it is only necessary to properly encode the measurements in digital form and to reliably record and playback the corresponding pulses.

To inject a note of realism into this discussion, we must recall that these high-order accuracies have meaning only if the transducers, which make the primary measurements, are capable of responding with such degrees of accuracy. The data-processing-system chain can be no stronger than its weakest link.

In some ways, the digital process is a simpler one than those previously discussed and presents fewer design problems. For example, the record (write) and reproduce (read) amplifiers can be quite elemental. The speed stability of the transport is not as important, since relatively large amounts of flutter and wow can be tolerated without effecting the recording accuracy.

We have other problems, however, which become more important in digital recording. Sensitivity to *tape dropout errors* is the most obvious one. Since all information is contained in the presence or absence of pulses on playback, we cannot tolerate the loss of pulses or the generation of spurious pulses caused by the tape imperfections. For this reason, special precautions are taken in the manufacture, inspection and selection of tape intended for digital recording. This does not completely solve the problem, however.

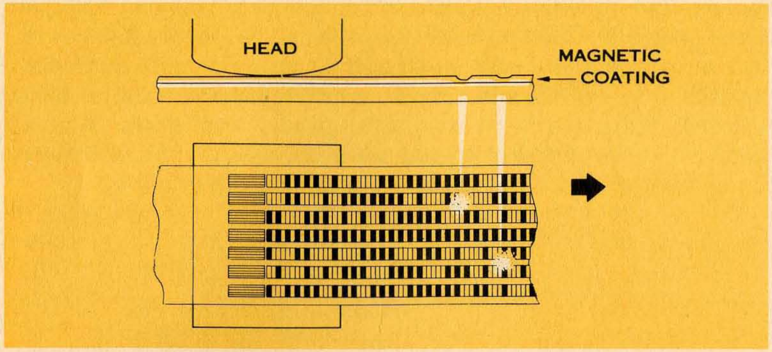


Fig. 24. Effect of drop-outs in digital recording.

As discussed under Direct Recording Process, tape dropouts become most critical at short wavelengths, those approaching the size of the gap in the reproduce head. This demands the use of moderately long pulses on the tape, or moderately low pulse-packing densities. A figure of 200 pulses per inch of tape has been commonly accepted as a conservative one for reliable digital recording.

Part of this same problem is the one of maintaining excellent head-to-tape contact to minimize the dropout effect. This requires an extremely fine finish on the surface of the head, adequate tape pressure, and a minimum tendency for the head to collect oxide particles from the surface of the tape. It goes without saying that cleanliness must be maintained in the environment and handling of a digital recorder and its tape.

There are additional safeguards which are often built into the Digital Recording Process to provide greater reliability against the possibility of tape dropouts or other errors. One of these is the use of *redundancy*, in which the same information is recorded twice (in whole or in part) on parallel, but separated, tracks on the tape. A second scheme is the use of a *parity check*, in which one track on the tape is reserved for a pulse which is derived from the pulses being recorded simultaneously on the other tracks. A parity pulse is recorded of such a polarity that the sum of all bits on playback (including the parity bit) will be an odd number. Thus an error will be indicated if *one* (or an *odd* number) of the pulses are lost. It will not detect *two* simultaneous errors (or an *even* number) of errors.

A second problem which assumes greater importance in digital recording is that of *tape skew*. This is any tendency for the center line of the tape to depart from a perpendicular to the line of record and reproduce head gaps. The reason for this is that the digits (or bits) making up a given number or character, are usually recorded in parallel fashion, all at the same time, each on a different track of the tape.

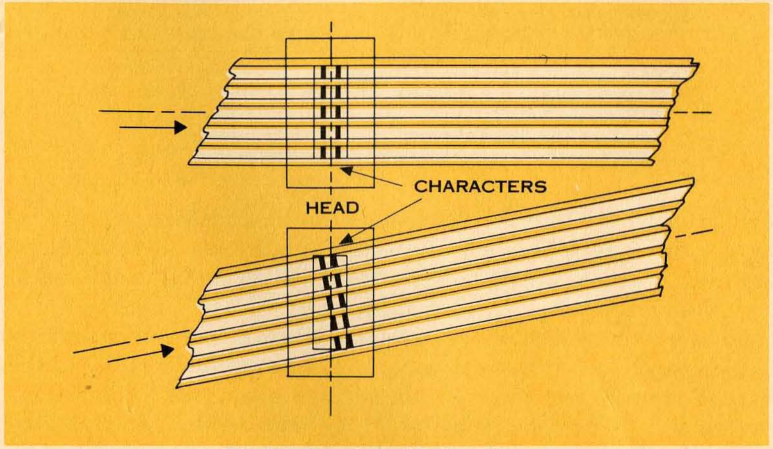


Fig. 25. Error caused by tape skew.

Figure 25 illustrates in exaggerated form the effect of tape skew in which the top and bottom head tracks would be reading bits from different characters at any given instant, instead of reading all the bits from a single character at one time. The preventive is to maintain excellent tape guiding in the design of the transport. This is one of the factors which also demands a conservative pulse-packing density, since the closer the pulses are packed together, the more important will become the possibility of errors due to tape skew.

Let us apply to digital recording our concept of the *figure of merit* for efficiency of tape utilization. We will assume a sampling rate of 6 data samples per sine wave (or highest-frequency component) of the signal to be recorded, as explained under the PDM recording process. We will assume a 1% accuracy, requiring 7 bits per data sample, as indicated above. We will use a pulse-packing density of 200 bits per inch.

$$\frac{200 \text{ (bits/inch)}}{6 \text{ (data samples/sine wave)} \times 7 \text{ (bits/sample)}} = 5 \text{ sine waves/inch}$$

Summarizing and comparing this result with that from the other recording processes:

Recording Process	*Tape Utilization* (sine wave cycles/inch)
Direct	1600
Frequency-Modulation	166
Pulse-Duration Modulation	40
Digital	5

From this we see that the efficiency of tape utilization is lower by far for the digital than for any of the other recording processes. It does, however, preserve the recorded data in the language of the digital computer and its output can be fed directly into a computer, where such operations as calibration, transducer linearization, scale factor corrections, etc., can be applied readily to the data. For these two reasons, where large quantities of data must be taken, it is customary to "edit" the data while still in analog form. This is sometimes done using quick-look graphic techniques. From a quick visual inspection, it is possible to screen and determine those selected portions of the data which have significance. These are then converted from the analog to the digital form and recorded for further refinement and computation.

Where the transducers have the capability of measuring to degrees of accuracy beyond that of the other recording processes, and where it is required to preserve this accuracy, the original information is recorded digitally. This requires either of two approaches. The first is the use of transducers whose output is in digital form (such transducers are still in the developmental stage). The second is to digitize the information from the transducers before recording it. This requires considerable electronic equipment (analog-to-digital converters) to be associated with the recorder; and it creates a weight, size, and complexity problem under certain conditions, such as when recording data in flight.

Applications of the Digital Recording Process

Let us summarize the *advantages* of the Digital Recording Process:

1. Inherent capability of extremely high orders of accuracies.
2. Recording relatively insensitive to tape transport speed instabilities.
3. Simple record and reproduce electronic circuitry.
4. Output information is in the proper form for feeding directly into digital computers.

The relative *disadvantages* of the Digital Recording Process can be summarized as follows:

1. Poor tape economy – 1/8th that of the PDM process and 1/30th that of the FM process.
2. Data must be digitized at the source, or special digital transducers must be employed.
3. Reliability extremely dependent on tape quality, requiring redundancy and parity-check features.

The applications of digital recording are primarily for the processing of edited data, involving digital-computer techniques; and as an input device, output device, and internal storage for digital computers.

MAGNETIC RECORD AND REPRODUCE HEADS

We are now ready to discuss the second basic element of a magnetic tape recorder—the *Magnetic Head.* It is no mere copywriter's slogan to refer to the magnetic head as the heart of a recorder. To manufacture a series of practical magnetic recorders, which can be universally used for instrumentation purposes, requires highly refined and precise production and quality-control techniques. The objective must be to produce heads having absolute uniformity of electrical and mechanical properties, to permit multiple track recordings to be interchanged from machine to machine without mechanical alignment or adjustment; to permit amplifiers to be substituted one for the other, and connected interchangeably from track to track without matching or tuning; and to permit any track to be used with any of the other four basic recording processes. And recalling the previous theoretical discussions, we recognize that most of the limitations of each of the recording processes are intimately related to specific characteristics of the magnetic heads.

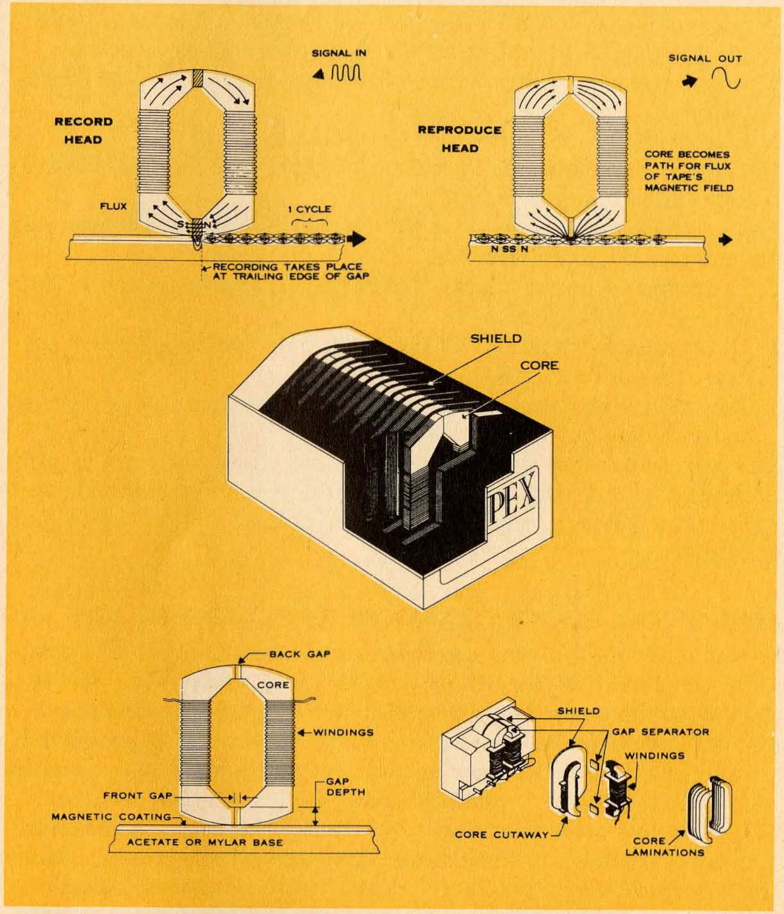


Fig. 26. Construction of a magnetic head.

Figure 26 illustrates the construction of a typical magnetic head. Two identical core halves are constructed of thin laminations of a material having high magnetic permeability, low electrical resistivity (to minimize eddy-current losses) and good physical-wear properties (for long head life). Each core is wound with an identical number of turns and assembled with non-magnetic separators for the front and back gaps. It is only the front gap which contacts the tape and actually enters into the recording process.

The rear gap maintains magnetic symmetry of the core halves and minimizes the effect of random hum pickup in the two windings, which are connected in phase opposition (for external magnetic fields).

For a *record head*, the gap size must be long enough to achieve deep flux penetration into the tape, and short enough to obtain sharp gradients of high-frequency bias flux at the trailing edge. A common value of gap width is one-half mil. The winding is designed so that the combination of current-carrying capacity (determined by wire size) and the number of turns gives sufficient ampere-turns to provide the necessary bias magnetization for Direct recording, or to saturate the tape for the other recording methods.

For a *reproduce head*, the gap size is a compromise between upper frequency limit, dynamic range and head life as previously explained under the Direct Recording Process. A one-quarter mil gap is commonly used. Since the output from the head is a direct function of the number of turns, it is advisable, in general, to wind as many turns as possible on the reproduce heads, using as fine a wire size as can be safely handled and give reliable service. The other limitation on the number of permissible turns is one imposed by electrical resonance occurring between the inductance of the head winding and the capacitance of the head cable. The resonant frequency must be kept above the useable top frequency of the recorder and is a limitation at the higher recording speeds (where higher recorded frequencies are involved). At lower tape speeds (involving lower frequencies) a lower resonant frequency can be tolerated, permitting more turns. Fortunately, the added turns are particularly helpful at the lower tape speeds, since the output voltage is proportionately lower at lower tape speeds. Thus it is possible to obtain a head which is optimized for low-speed operation by putting more turns on the winding.

The first parameters which must be established in a multi-track magnetic head are *standards* of *track width* and *track spacing*. The conflicting factors which must be resolved in establishing such standards are: maximum utilization of the tape (which would indicate narrow tracks closely spaced); good signal-to-noise characteristics (which would indicate wide tracks for maximum signal output); and minimum crosstalk between tracks (which would indicate generous spacing between tracks). Two factors enter into the problem of crosstalk between tracks. The first is the interaction between the fluxes actually recorded on adjacent tracks of the tape. The second is the electromagnetic and electrostatic coupling between the windings on adjacent head units in a multihead stack. It is the second of these which is the most critical, requiring not just physical separation, but the insertion of effective shielding in the space between head units.

Optimum balance of these conflicting factors has resulted in the establishment of the following standards of track width and track spacing, which are in common and widespread use today. Track widths are 50 mils. Center-to-center track spacing on the tape is 70 mils. Center-to-center spacing in any given head stack is 140 mils. This is illustrated in Figure 27 and shows how it is possible, by using two head stacks and by *inter-leaving* the tracks, to achieve the desired end result of good tape utilization with adequate separation between head units in a stack. Alternate layers of Mu-metal and copper are inserted between head units in a stack to give the necessary electromagnetic and electrostatic shielding; and to hold crosstalk below the inherent noise level of the system. These standards permit the recording of 7 tracks on a ½-inch tape, or 14 tracks on a 1-inch tape.

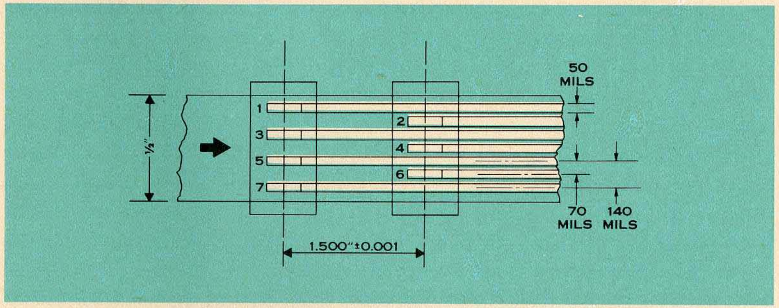


Fig. 27. Head standard.

The two head stacks making up a set are precisely positioned—one relative to the other, so that the distance between the two lines passing through the center lines of the gaps is exactly 1.500 inches within a tolerance of ±0.001 inches. This establishes the *relative timing accuracy* between information channels recorded on separate stacks—but it must be realized that this relation is subject to error resulting from tape stretch or shrinkage, which can occur with changes in temperature or humidity. For this reason, it is customary to record information channels on the same head stack where more precise inter-channel timing accuracy is required. The other alternative is to use a single stack of heads on a wider tape, as for example, 7 tracks on a 1-inch tape, or 4 or 3 tracks on a ½-inch tape.

For the reasons described under the Digital Recording Process, interleaved tracks on multiple heads would be unsuitable for digital recording. Here, however, the requirement for dynamic range (and crosstalk) are much less severe, permitting closer track spacing. Thus, digital recording heads can successfully use as many as 16 tracks to the inch with a single head stack.

In assembling a multi-track head, it is essential to maintain close tolerance on the electric characteristics (such as inductance and number of turns) to insure uniformity of response from track-to-track and from machine-to-machine. It is also essential to maintain extremely close mechanical tolerances on gap scatter (to minimize interchannel timing errors), and on gap-azimuth angle (to avoid deterioration of high-frequency response). Tolerances which should be maintained in production to achieve these results are shown in Figure 28.

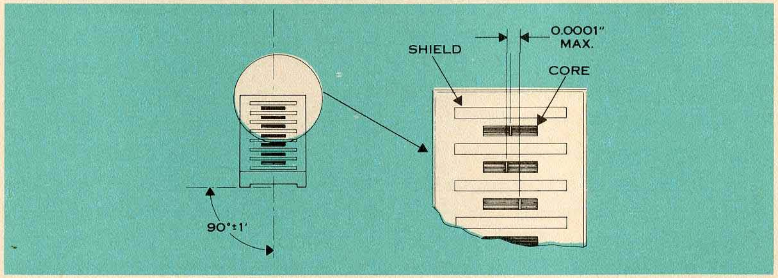


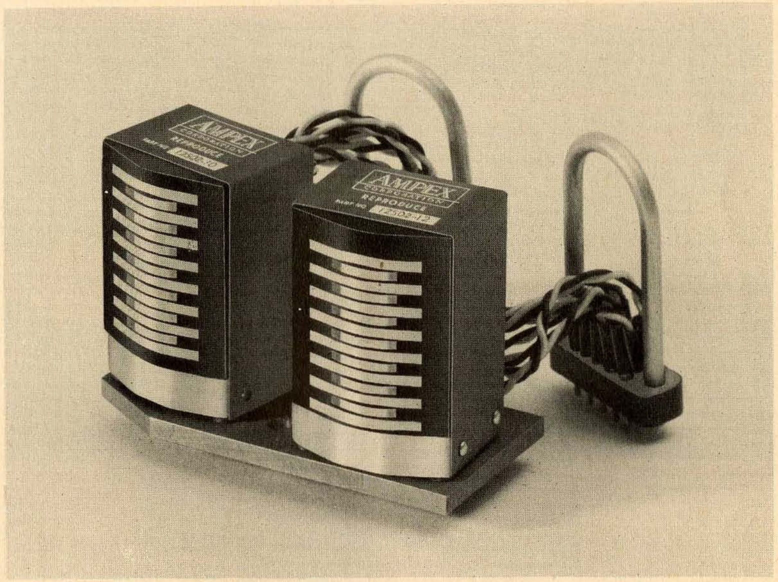
Fig. 28. Mechanical tolerances.

The total gap scatter for all heads in a given stack should be less than 100 microinches. This 100-microinch band, shown in Figure 28, is defined as including the trailing edges of the gaps for a record head, and the center-lines of the gaps for a reproduce head. The azimuth alignment of the line through the gaps should be aligned relative to precision-milled mounting pads, so that when the head is assembled on a precision mounting base, it will be perpendicular to that base plate within ±1 minute of arc. This head assembly can then be inserted in the recorder without requiring any further alignment or mechanical adjustment.

One further element of the magnetic head requires special attention. This is the *surface of the head* which contacts the tape. The smoothness of this surface is extremely important in maintaining intimate head-to-tape contact to insure good high-frequency response, minimum sensitivity to tape dropout errors and minimum tendency to accumulate tape oxide deposits. In addition, the shape of the contour is of importance at low frequencies, or long wavelengths, to avoid interaction between the head windings and regions of the tape, other than that which lies within the actual reproduce gap. Such interactions result in anomalies or "bumps" in the low-frequency response curve. To achieve careful control of the surface contour and to produce smooth surface finishes in the order of microns requires very special head-polishing machinery and production techniques.

Illust. 5 is a photograph of a 14-track head assembly made up of two interleaved stacks mounted on a precision base plate. Electrical connections are provided for each stack. You can observe the full-width shielding which exists between the individual head tracks. The combination of the electrical connectors and the precision base plate makes it possible to quickly and simply replace a head on a tape transport, without any mechanical adjustment and without the necessity of disconnecting a multitude of individual head cables from the amplifiers into which they feed.

The foregoing discussions should give some appreciation of the special skills and techniques required to make, on a *production basis*, magnetic heads suitable for instrumentation recording use. The performance of the entire recording system is so much a direct function of the heads, that each head should be assigned an individual serial number and a complete record maintained of

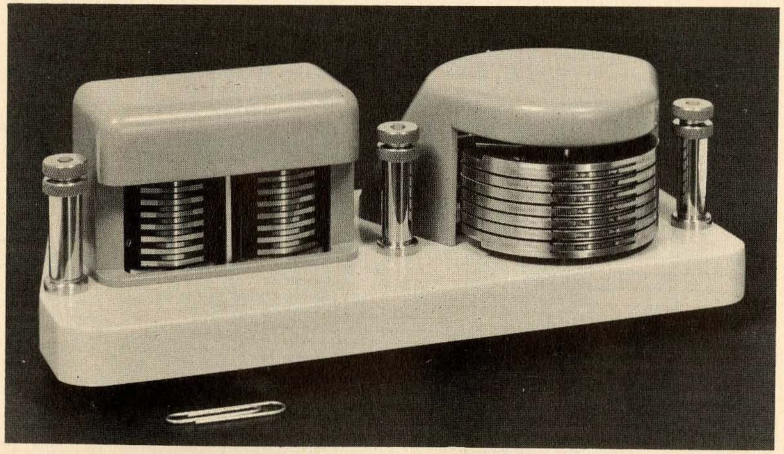


Illust. 5. Fourteen-track head assembly.

its mechanical and electrical characteristics. Using such a procedure, as part of a rigid quality-control system, will insure that tapes made on one recorder can be played back any time, any place, on any other similar recorder, with the confidence that specification performance can be met.

Movable Magnetic Heads

In the foregoing discussion, I emphasized the importance of maintaining accurate alignment of all head gaps in a multi-track head stack for relative inter-channel timing accuracy. There are cases, however, where it would be desirable to be able to vary the relative gap positions of a multi-track head, so as to introduce controlled timing delays between signals recorded on parallel tracks. Illust. 6 is a picture of a special movable-head assembly designed for this purpose. We see a rear view of the head assembly, showing the levers which permit independent adjustment of the individual heads. Each head gap can be advanced or retarded up to ¾-inch from its center position. This will allow controlled variable time-



Illust. 6. Movable magnetic heads.

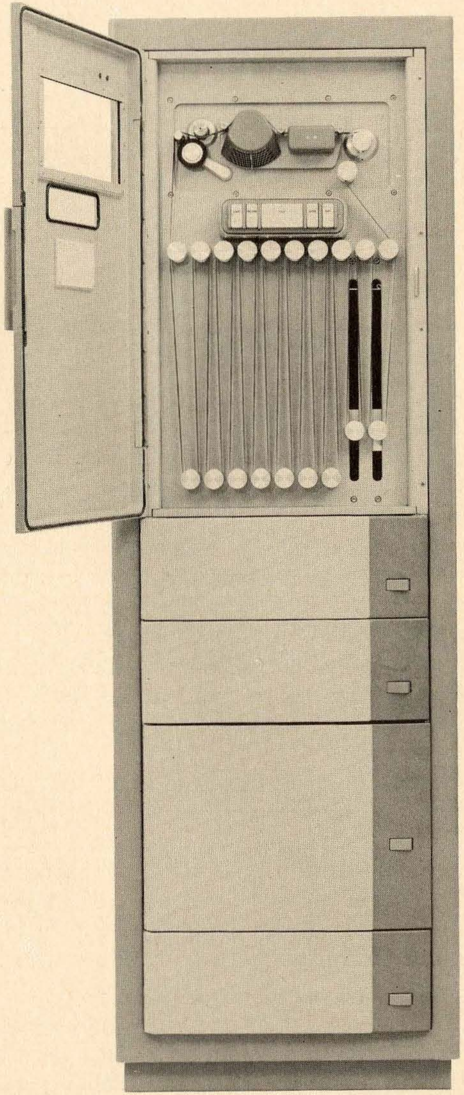
delays between tracks up to 40 milliseconds (at a 30-ips tape speed), and proportionately longer delays at lower tape speeds. With a head of this type, auto-correlation and cross-correlation techniques can be applied to the analysis of data signals which are obscured in a high background-noise level.

Illust. 7 shows this movable-head assembly being used for this purpose, as part of a tape-loop transport.

MAGNETIC TAPE TRANSPORTS

We come now to the third and final basic component of a magnetic tape recorder—the *tape transport*—shown in simplified form in Figure 29. The elements involved in this simple version of a tape transport are the following (in the order in which they are contacted by the tape):

A. *Supply Reel*—feeds out tape and provides hold-back tension to insure intimate contact of the tape with the heads. Fitted with a motor for rewinding the tape, and a brake to decelerate the reel rapidly and smoothly when tape motion is stopped. Hold-back tension can be derived by either energizing the rewind motor in an opposing direction, by applying the brakes, or by a combination of both means.



Illust. 7. Magnetic tape loop analysis system using a movable head.

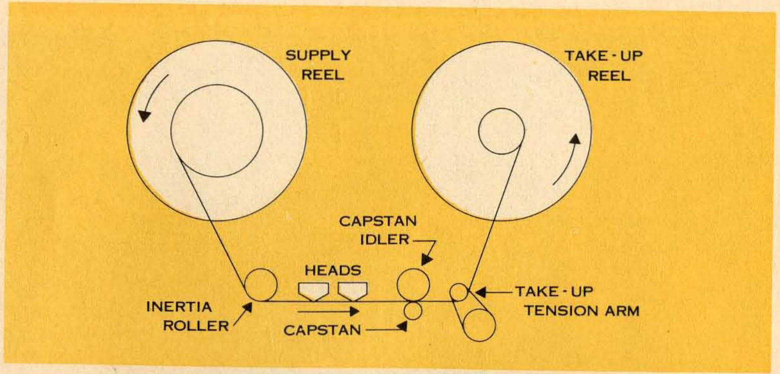


Fig. 29. Simplified tape transport.

B. *Inertia Roller*—connected to a flywheel and serves to smooth out variations in tape speed which could be caused by uneven torque or motion of the supply reel.

C. *Magnetic Record and Reproduce Heads*—whose function has already been described.

D. *Capstan*—"meters" the tape at a constant linear velocity. Is driven by a constant-speed synchronous motor. Pressure between the tape and the capstan is maintained by a solenoid-operated spring-loaded capstan idler.

E. *Take-up Tension Arm*—is spring loaded to take up the normal slack caused when tape motion is first started until the take-up reel starts moving. This arm also serves to stop tape motion in the event of tape breakage.

F. *Take-up Reel*—takes up tape during normal playing and provides for fast-forward tape motion when shuttling tape. Provided with a motor for this purpose and with a brake to decelerate the reel rapidly and smoothly when tape motion is stopped.

This is obviously an over-simplified description of a tape transport. Other factors which must be taken into consideration in designing and constructing a tape transport are such things as:

1. *Differential braking forces*—to insure that when the reels are decelerated, the tape tension will not at any time exceed its safe elastic limit; nor, on the other hand, will a slack loop be formed which would either turn off the safety switch or snap the tape when started. This requires the braking force on the supply reel to be slightly greater by a carefully controlled amount, than that on the take-up reel; and this differential must be maintained within proper limits in either direction of tape travel (fast-forward or re-wind) for various combinations of full and empty reels.

2. *Tape hold-back tension*—if hold-back tension is maintained by energizing the supply-reel motor, the actual tension will vary inversely with the diameter of tape on the reel. Proper allowance must be made to insure that the tape tension, under these widely varying conditions, does not become too low for proper head contact—or so high as to deform the tape.

3. *Tape guiding*—suitable means must be provided in the form of fixed or rotary tape guides to maintain proper tape tracking (alignment of the tracks on the tape with tracks on the head) and to minimize any tendency for the tape to "skew."

The most important single design consideration in a tape transport is to insure that a *precisely constant speed* of tape across the heads is maintained at all times. This requires reducing to an absolute minimum any factor which could introduce tape-speed variations. Examples are the following:

1. The capstan is the most critical element, since it directly controls the tape speed. To maintain a timing accuracy of ¼% in a recording made on one machine and played back on another requires a capstan whose diameter is held to a tolerance of ⅛% on both recorders.

2. Any eccentricity or run-out of the capstan, or the pulleys connecting the drive motor to the capstan, or any bearing irregularities in the shafts of these components, would introduce a corresponding periodic speed variation in the tape. Similarly, eccentricities, run-outs, or bearing irregularities of any other rotating parts contacting the tape would reflect themselves into the tape motion. This applies to the capstan idler, inertia idler, rotary tape guides, etc. Extremely small run-out tolerances are required to be held in production. Pulleys must usually be ground to their final dimensions when assembled on their motors or shafts. A most careful selection of bearings is also required to insure smoothness of motion.

3. Speed errors will be introduced by variations in tape tension. These may be due to the changes in tape tension caused from full to empty reel, or they may be the result of rapid changes in tension

caused by uneven winding of the tape on the reels. It is desirable to introduce a positive control over tape tension, as for example, by the use of a tape-tension-sensing arm connected to a simple mechanical servo system working on the hold-back brake.

4. The design of the motor, particularly the capstan drive motor, should minimize any tendency for "cogging" or "hunting" when stable tape motion is achieved.

Flutter and Wow

The speed variations which we have discussed are usually expressed in terms of *flutter and wow*. These are terms established in the audio recording field and generally used in instrumentation recording as well. The accepted method of recording flutter and wow for audio purposes is to record a 3000-cps sine-wave signal on the recorder under test. This is then played back into a flutter bridge which consists of a limiter, discriminator and meter. Any flutter and wow in the recorder would modulate the 3000-cps signal and result in a reading on the meter. Generally, only those flutter components up to 300 cps are measured. And the measurement is made on an rms basis.

The above procedure is unsatisfactory for instrumentation recording purposes. First, the flutter-frequency components above 300 cps are equally important in their effect on the recorded data; and secondly, a peak-to-peak value of the modulation components is of far more significance than the rms value. Referring to Figure 30, representing a sine-wave flutter component, we see that a one-volt rms reading corresponds to a 2.8-volt peak-to-peak value. On nonsinusoidal wave forms of the type frequently encountered in recorders, the difference would be even greater.

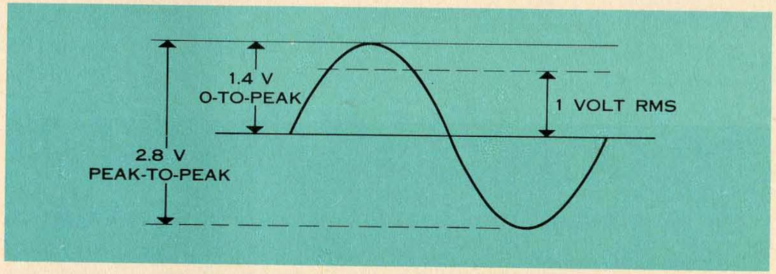


Fig. 30. Relation between RMS and peak flutter.

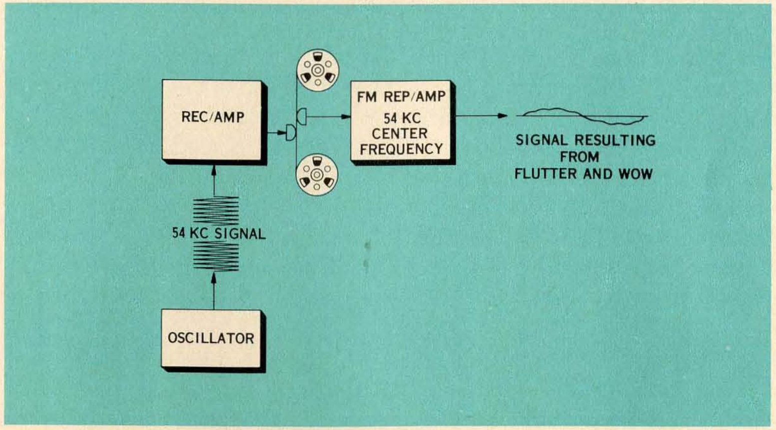


Fig. 31. System used to read effects of flutter and wow.

For instrumentation recording, it is common to make flutter-and-wow measurements by using an FM-record amplifier with an unmodulated 54 Kc carrier (the center frequency corresponding to 60-ips tape speed). The modulation products introduced by flutter and wow are presented to an oscilloscope, where instantaneous peak-to-peak values can be observed and measured, far beyond the dynamic-response capabilities of any electrical meter movement. The readings are taken and plotted on a cumulative basis, using a low-pass filter having a cutoff frequency which can be opened up progressively to 10 Kc.

Flutter and wow has the effect of introducing noise into an FM recording, introducing error into a PDM recording, and distorting the time base of any recording. It is this last factor, that of *time-base distortion*, which has considerable significance in instrumentation recording. Two forms of time-base distortion are encountered, aside from those associated with imperfections in the tape transport. One is a dynamic, or rapidly varying error, the other is a quasi-static or relatively slowly varying error. These will be discussed in turn.

Time-Base Distortion (Dynamic—due to tape "stiction")

Let us assume we have a "perfect" tape transport in which the possible tape-speed errors, described above, have been eliminated.

We would have a source of tape-speed error still remaining, which could not be eliminated from the transport in Figure 29. The tape drive system redrawn in Figure 32A is called an "open loop" drive, due to the unsupported loop of tape existing between the reproduce head and the capstan. This loop represents a distributed mass under tension, which has its own natural period of vibration. Longitudinal vibrations are induced in the loop due to the tape scraping along the heads, this scraping effect sometimes being referred to as "stiction" between the tape and heads. The vibrations which result are often called the "violin-string" effect. It causes an increase in flutter and wow which reaches a peak at the resonant frequency of the loop, usually in the region of 2500 cps. This effect can be reduced considerably by the use of another method of tape drive—the "closed loop," as shown in Figure 32B. Here the tape is formed into a tight closed loop, and is driven by two capstan idlers bearing on either side of the capstan. The record and reproduce heads are located inside the loop on opposite sides of the loop. A low-inertia turn-around idler accomplishes reversal of tape direction inside the loop.

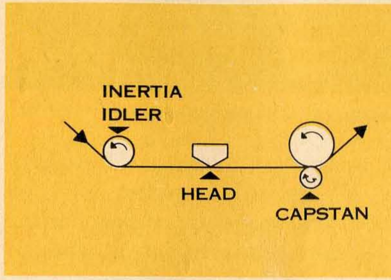


Fig. 32a. Open-loop tape drive.

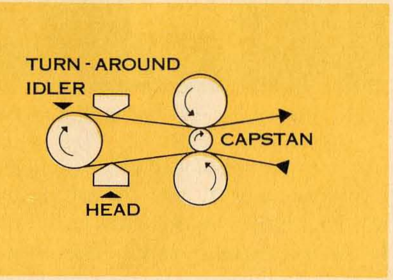


Fig. 32b. Closed-loop tape drive.

The first obvious advantage of the *closed-loop drive* is the reduction in length of unsupported tape to a much smaller value. The resonant frequency associated with this shorter length occurs at a higher frequency and at a reduced amplitude, where its effect on flutter is much less serious. Other advantages are the more effective isolation of tape-speed effects reaching the heads, caused by reel-torque variations or other effects occurring outside of the closed loop.

Time-Base Distortion (Quasi-Static)

There are other sources of time-base distortion which can result from influences completely external to the tape recorder. We will catalog these as "*quasi-static*," since they do not change rapidly with time. These sources of errors are:

1. *Power-Supply Frequency.* Since the speed of the capstan is determined by the synchronous motor which drives it, any change in power-supply frequency from the recorder to the reproducer would cause a directly proportional change in tape speed and recorded time-base.

2. *Tape Dimensions.* Changes in humidity and temperature between the time of recording and reproduction will cause changes in the length of the tape, distorting the time base, even though the tape speed remains the same. Mylar-based tape is much less sensitive to these effects than is acetate-based tape, but the effects must still be reckoned with where accuracy of time base or accuracy of recorded frequency must be preserved. Differences in tape tension between machines can cause similar errors.

It is possible to overcome these "quasi-static" errors in time base by employing a *Servo Speed Control System.* This is accomplished by recording on one track of the tape a reference signal derived from an accurate, constant-frequency 60-cycle source.

Such a source could be a tuning fork, Wien-bridge oscillator, or crystal-controlled oscillator with frequency dividers. This 60-cycle reference tone is usually used to amplitude modulate a higher-frequency carrier (e.g. 18.25 Kc) which is the signal actually recorded on the tape. The rest of the frequency spectrum on the track can be used for recording other data.

On playback, the modulated carrier is demodulated, recovering the reference tone. This is then phase-compared with a second accurate constant-frequency 60-cycle signal source, and any difference in phase is applied as an error signal to a capstan motor drive amplifier. This amplifier delivers power to the motor at a frequency which differs from 60 cycles by the necessary amount to insure that the playback reference signal will always be exactly 60 cycles—regardless of any error which may have occurred in tape length. It is also entirely independent of the frequency in the power line.

Thus, by use of a servo system and a constant-frequency source of power, time-base accuracy can be maintained as follows:

1. On a long-term basis, accuracy is limited only by the combined error introduced by the two frequency standards. Crystal-controlled frequency standards with accuracies of two parts in 100,000 are available as standard equipment.

2. On a short-term basis, the servo system can be made "tight" enough to hold the maximum instantaneous time-base error to less than a millisecond, and can be made to respond rapidly enough to overcome disturbances occurring at rates up to one-half cycle per second.

Possible Variations in Tape Transport Design

There are a wide variety of forms which a tape transport can take —determined by the particular application which it is intended to serve. Some of these possible variations are:

1. *Various Tape Speeds.* Depending on the frequency bandwidth desired for any particular method of recording, tape speeds may vary over a range from 0.1 inches per second to 120 ips. Recorders intended for a variety of possible applications are usually designed to accommodate a number of tape speeds, the most common of which are 1⅞, 3¾, 7½, 15, 30, and 60 ips.

2. *Form of Recording Medium.* The recorder can be designed to accommodate a variety of possible medium forms, such as:

   (1) The conventional reel-to-reel form is as sketched in Figure 29;

   (2) The form of a continuous drum, for constant repetition of short-duration signals (Illust. 8 and 9 show the front and rear views of a drum recorder employing a 2-inch-wide strip of tape formed around the surface of a cylinder. This recorder was designed for use in geophysical exploration for the recording and subsequent analysis of the output of 26 geophones);

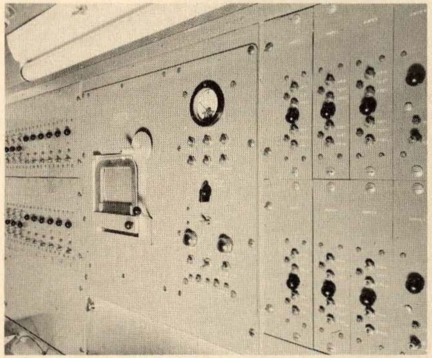
   (3) The form of an endless loop, as shown in Illust. 10. (Such a device can be used for repetitive playback of a transient signal for spectrum analysis, or as a time-delay device for storing an instantaneous signal, such as a lightning transient, an electric power-line fault, or a radar-return pulse, until it can be re-recorded onto a reel-to-reel recorder.)

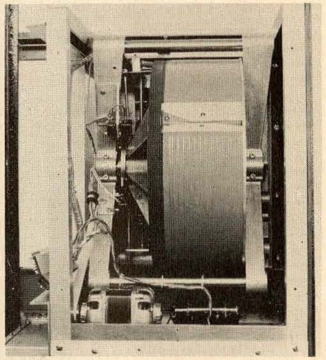
3. *Varying Tape Widths.* Depending on the number of tracks to be recorded, tape transports can be designed to accommodate tape widths of ¼, ½, or 1 inch.

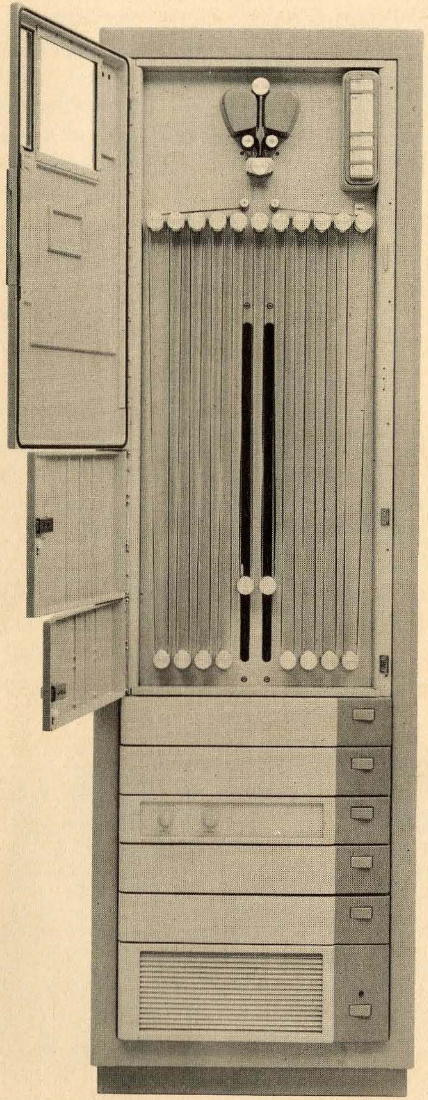
4. *Reel Sizes.* Depending on the playing time desired for a given tape speed, a tape transport can be designed to accommodate various-sized reels. A 10½-inch-diameter reel, containing 2500 feet of standard-base tape (0.015-inch thick) is most commonly used. This gives a recording time of 16 minutes at a 30-ips tape speed. Using thin-base Mylar tape (0.001-inch thick), this recording time can be increased by 50%. A 14-inch-diameter reel will accommodate 5000 feet of standard-base tape. Illust. 11 shows a machine using 19-inch-diameter reels holding 10,000 feet of 1-inch tape.

Special Characteristics:

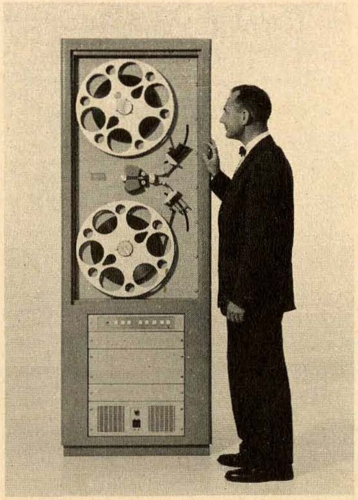
(1) *Digital Transports.* Illust. 12 illustrates a digital transport having extremely fast start and stop characteristics. For digital recording, information is usually put on the tape intermittently in the form of relatively short blocks, corresponding to a "word" or a group of "words." In order to utilize the tape most efficiently without long blank spaces between "words," rapid acceleration and deceleration of the tape is essential. The transport shown can come from rest to full recording speed in just a few milliseconds and can stop in the same time.


Illust. 8. Drum recorder for geophysical applications (front view).

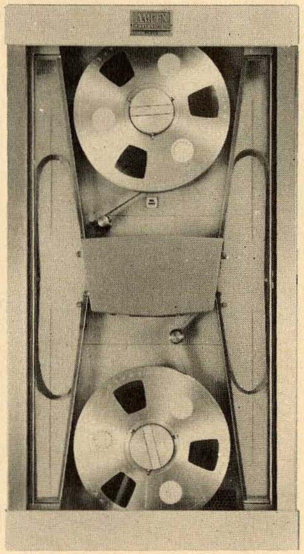

Illust. 9. Drum recorder for geophysical applications (rear view).



Illust. 10. Continuous loop recorder for transient analysis and time-delay application.

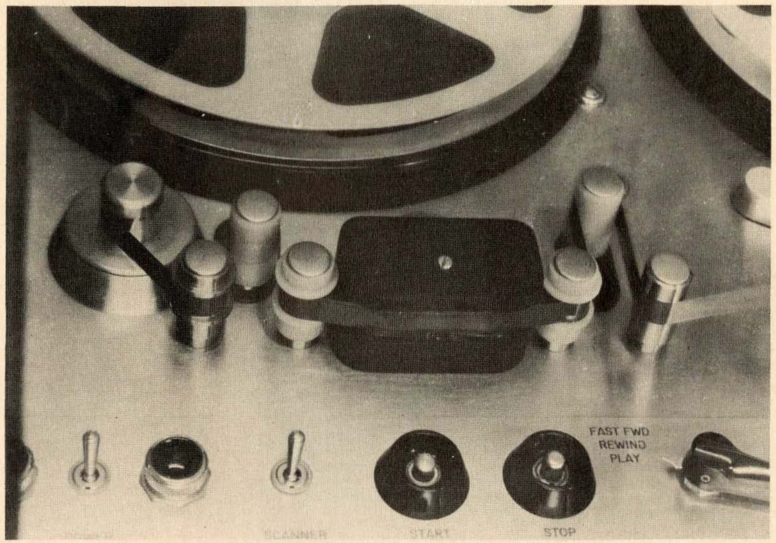


Illust. 11. Recorder employing 19-inch-diameter reels for long playing times.

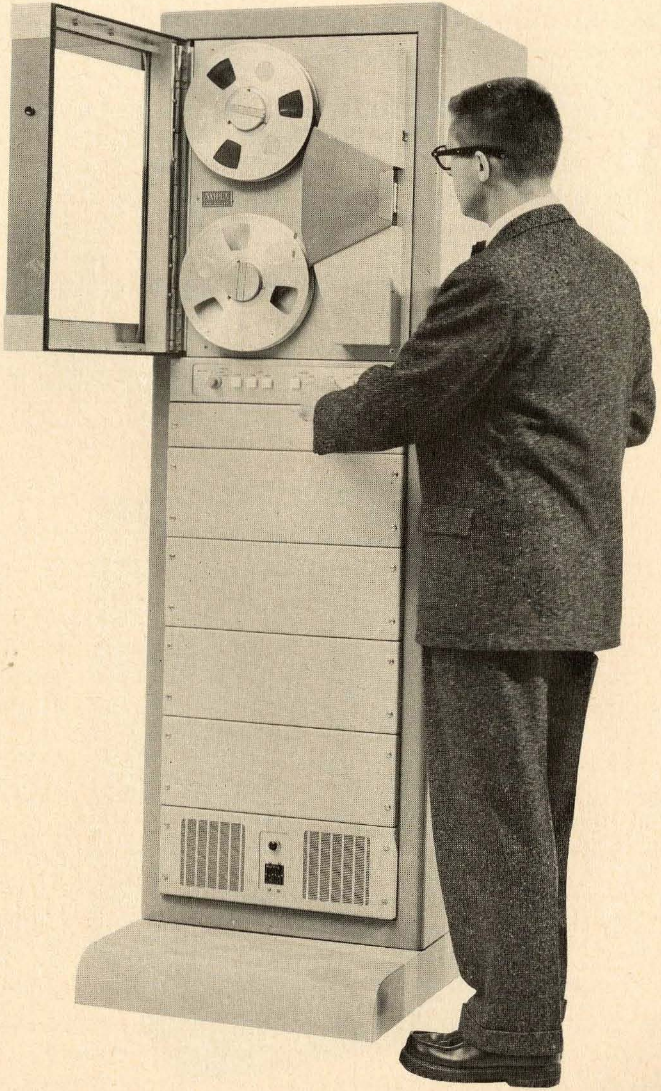


Illust. 12. Digital tape transport.

(2) *Tape Scanner.* Illust. 13 shows an interesting version of a special recorder, called a "Tape Scanner." It permits playing back repetitively a fixed segment of the tape (1 inch in length) even when the reel-to-reel motion is stopped. The tape passes over two special moving idlers on either side of the head. These idlers are connected to opposite ends of a pivoted bar, which causes the idlers to oscillate about the pivot point. This imparts an oscillating motion to the tape which "shuttles" itself back and forth across the head. The amplifiers are gated once each cycle of motion to readout the reproduced signal during that portion of the tape-travel cycle when the tape is moving in a forward direction at constant speed across the head. This repetitive readout signal can be synchronized with the sweep of an oscilloscope to permit a continuous visual observation of the signal on the 1-inch piece of tape being scanned. The reel-to-reel motion can be started at a slow rate and superimposed on the scanning motion to give a continuously moving visual presentation of the signal on the tape as it proceeds through the machine.



Illust. 13. Tape scanner.

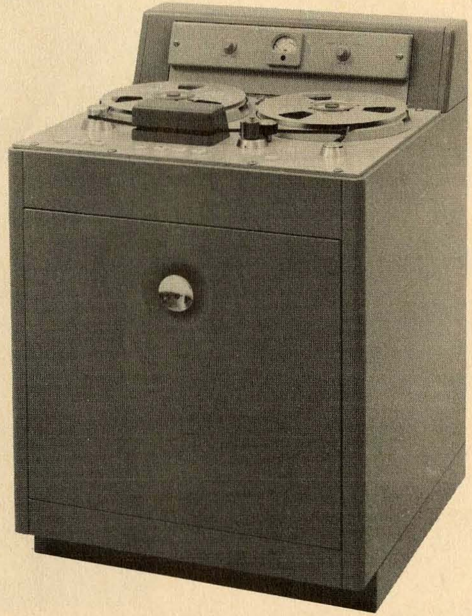


Illust. 14. Rack-mounted tape recorder.

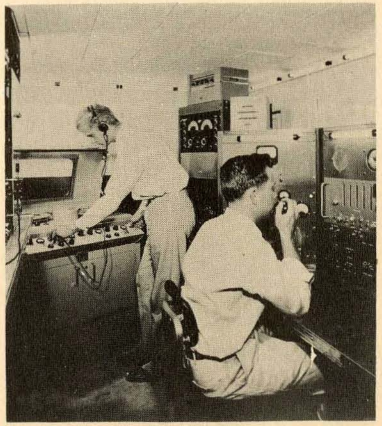
Effect of Environment on Recorder Design

Other variations in the tape-transport design result from the particular environmental conditions under which the recorder must be operated.

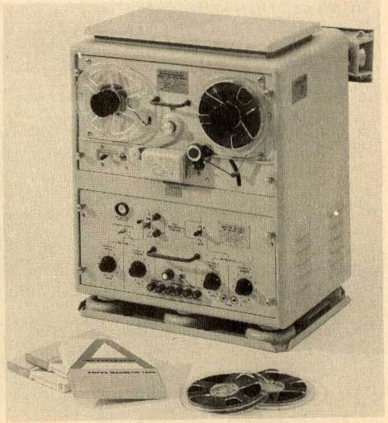
1. *Laboratory Recorders.* The usual packaging of a recorder for a fixed or laboratory installation is in the form of a rack, as shown in Illust. 14. For certain applications, a console mounting provides greater operating convenience, as shown in Illust. 15.
2. *Portable Recorders.* For field use, recorders can be packaged in portable carrying cases.
3. *Mobile Recorders.* There are many applications for mobile recorders requiring operation under extremely adverse environmental conditions, involving shock, vibration, extreme temperatures, or desert atmospheres. Illust. 16 shows a ruggedly designed unit installed in a mobile van being used as part of a telemetry system.



Illust. 15. Console-mounted tape recorder.



Illust. 16. Ruggedized recorder in a mobile application (part of telemetry van).

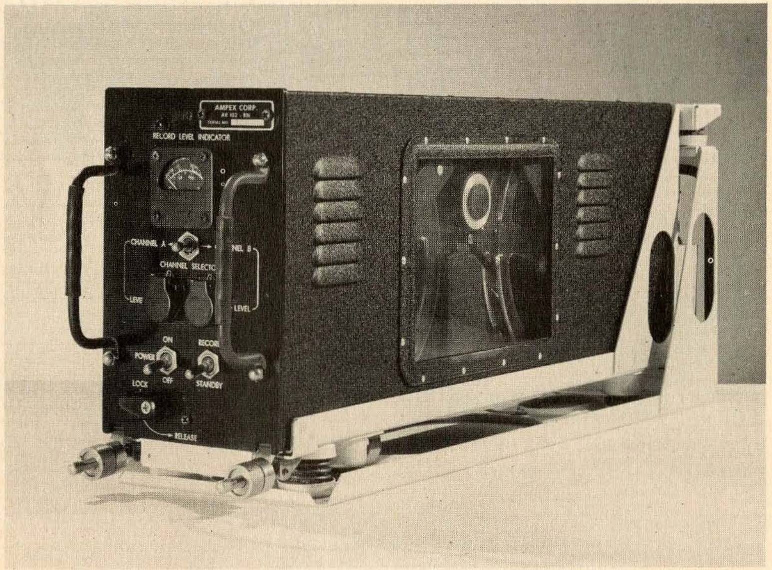


Illust. 17. Navy shipboard recorder model AN/UNQ-7.

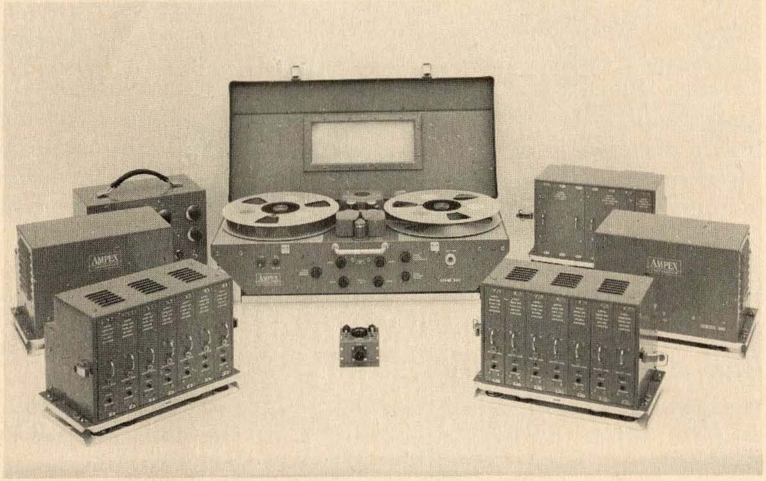
4. *Shipboard Recorders.* Illust. 17 illustrates a special Navy recorder, the AN/UNQ-7, designed for reliable and accurate recording aboard ship under the extreme environmental conditions encountered at sea.
5. *Airborne Recorders.* Illust. 18 is a specially compact Navy recorder, Model AR-102, designed for use in naval aircraft, having performance characteristics similar to the AN/UNQ-7 shipboard recorder. Illust. 19 is a precision airborne instrumentation recorder with its associated electronic components. This recording system permits the recording of multi-track signal information in either Direct, FM, or PDM forms. It contains its own precision frequency source to insure precise tape speeds, independent of the varying voltages and frequencies of the airplane power supply. Such recorders must be designed to meet the stringent requirements of military specifications, and must use MIL-approved construction and components throughout.

General-Purpose Laboratory Instrumentation Recorder

We have outlined the many variations possible in a magnetic tape recorder. While the art was evolving, it was the usual practice to custom design and produce a succession of special recorders, each tailored to the particular application at hand. This made it difficult



Illust. 18. Navy airborne recorder model AR-102.



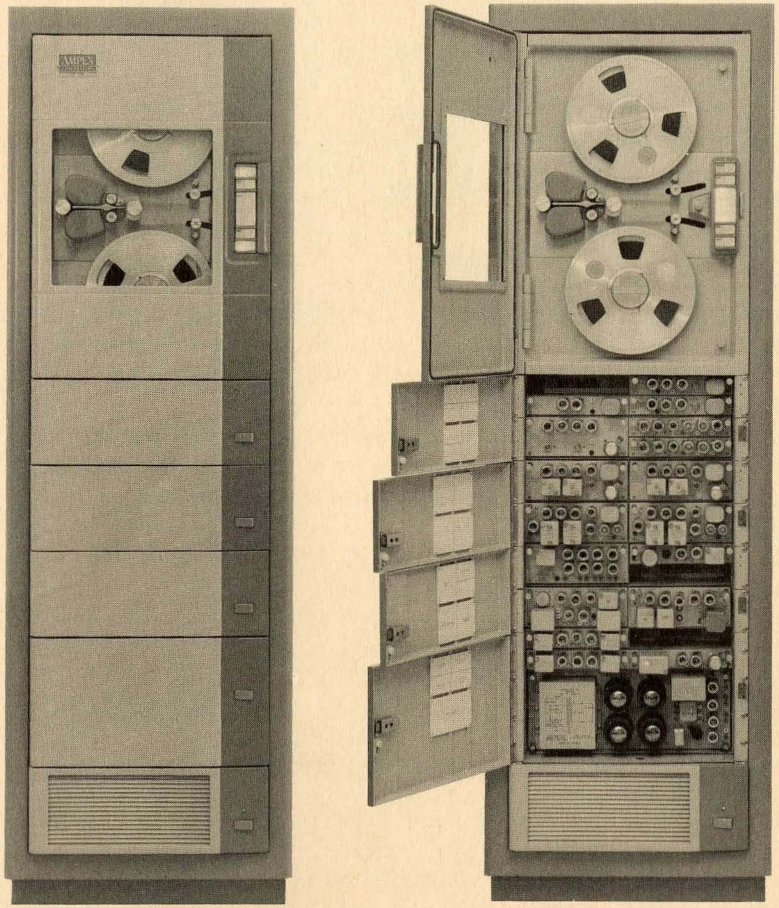
Illust. 19. Airborne instrumentation recording system.

to develop standard production and quality-control procedures. More than that, it committed and limited the machine to certain performance capabilities; and rendered it difficult to adapt to different recording methods, different tape speeds, system expansion, etc., as the particular application expanded or changed.

As a result of the vast accumulation of experience in building recorders of various types for a wide variety of applications, it is now possible to produce a general-purpose laboratory recorder having a high degree of inherent versatility. Into such a recorder can be designed the capacity for readily accommodating a host of possible recording applications (using different types of recording methods and tape speeds) and permitting later system expansion. The advantages to a user are obvious, since he is provided with an investment which will not become obsolete as his recording problems change—and where one recorder can be purchased to do the job of several specialized recorders. The advantages to the manufacturer are equally obvious, wherein orderly production methods and testing techniques can be employed. These advantages result in further benefits to the user in the form of economies, quality and uniformity.

Illust. 20A and 20B show such a general-purpose instrumentation recorder, featuring such operating conveniences as the following:

1. *Six tape speeds* (covering a range of 32 to 1) any of which can be selected simply.
2. *Plug-in record and reproduce amplifiers* available in either Direct, FM, PDM or Digital form. Any one recording method, or any combination of recording methods, is possible by plugging in the appropriate amplifiers.
3. *Plug-in power supplies* (mounted in the rear) all interchangeable and each capable of powering 4 record amplifiers or 2 reproduce amplifiers.
4. *Plug-in precision head assemblies,* quickly replaceable, requiring no adjustment.
5. *Hinge-mounted tape transport* for ready accessibility to the mechanism.
6. *Constant tape tension,* controlled by a mechanical servo system acting on the brakes.
7. *Closed-loop tape drive,* resulting in extremely low values of flutter (less than 0.1% peak-to-peak cumulative up to 500 cps).



Illust. 20. General-purpose instrumentation recorder.

8. *Efficient cooling system* permitting compact design of electronic assemblies.
9. *Built to MIL-specifications* and employing MIL-approved components.

Available accessories include servo speed control, meter panels and attenuator panels.

The availability of standard equipment of this type has broadened the frontiers of the tape-recording art. It has served to accelerate the introduction and acceptance of recorders in many new and significant applications. Some of these will now be described.

SOME INTERESTING APPLICATIONS OF MAGNETIC TAPE RECORDERS

The unique properties of the magnetic recording technique have opened the door to a number of unusual and interesting applications of magnetic recording.

Time-Base Changes

One of the properties we have mentioned is the *ability to alter the time base.* Thus, a signal or an event can be recorded at one tape speed and played back at a different speed. In this way, an event can be recreated on a compressed or expanded time scale. There are many ways this technique can be used to advantage.

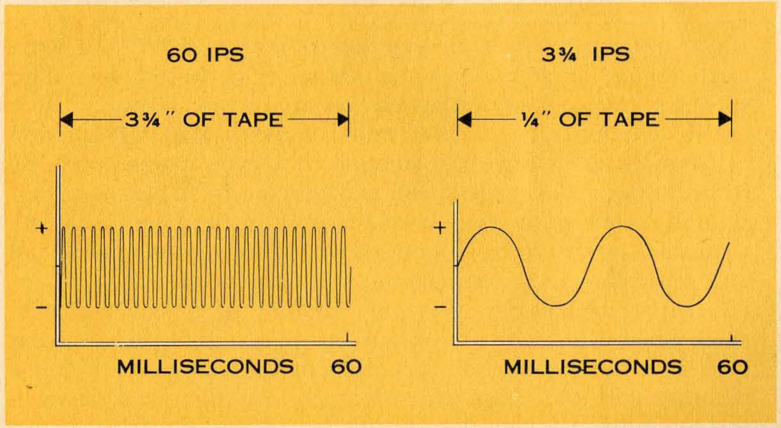


Fig. 33. Time-base alteration of a 480 CPS sine wave.

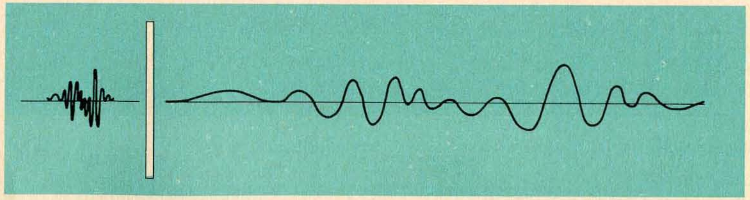


Fig. 34. 1:8 time-base expansion.

(1) *Graphic recording of fast transients or high-frequency signals.* Often it is desired to obtain a pen-and-ink or other graphic recording of a fast transient or high-frequency signal which occurs or varies at too fast a rate for the graphic recorder to follow. This is accomplished by tape recording at a high tape speed and playing back at a low speed. Slowdowns of 1000 times or more can be obtained by successive re-recordings.

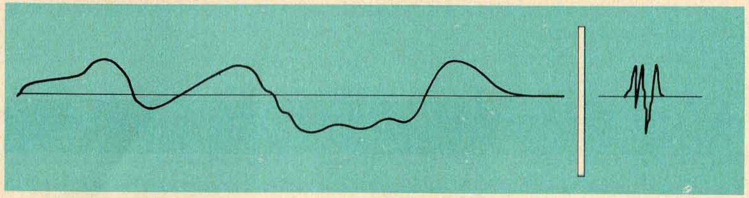


Fig. 35. 16:1 time-base contraction.

(2) *Spectrum analysis of very-low-frequency signals.* In some applications, as in under-water sound, it is desired to obtain spectrum analysis of extremely-low-frequency signals. There are no commercially available signal analyzers that will function at frequencies as low as a fraction of a cycle per second. By recording at a slow tape speed and playing back fast, it is possible to compress the time-base and multiply all frequencies by a constant factor which will put them in the range of commercial and practical spectrum-analyzing equipment.

(3) *Input devices for electronic computers.* There are occasions when it is desired to use an analog computer for an event occurring too rapidly for the speed of the computer. Using a recorder with time-base expansion can slow the event down to the computer's capabilities. In other cases, it is desired to make

most effective utilization of a high-speed digital computer for relatively slow events. Here the signal can be recorded in advance, and the time-base can be compressed for programming it into the computer.

Tape Loop Applications

In Illust. 10 we show the picture of an *endless loop of tape.* Such a device serves as a useful tool in such applications as the following:

(1) *Spectrum analysis of a transient signal.* A transient signal is difficult to spectrum analyze because the time response of a narrow-band filter is too short to give any significant output from a short-duration transient. By recording the transient on an endless loop of tape and playing it back repetitively, spectrum analysis can be accomplished.

(2) *Time delay of an incoming signal.* Let us assume we wish to record a signal which may occur instantaneously, but at completely random and unpredictable intervals. Examples of such signals could be lightning flashes, electric power-line faults, or radar-return pulses. If we kept a conventional reel-to-reel recorder running continuously so that such a signal could be recorded when received, we would use large quantities of tape medium, having long blank periods of no signal information. On the other hand, if we use a relay which would turn the recorder on when a signal was received, we would miss an important part of the signal while the recorder was coming up to speed. A tape loop can be used to provide a solution, as sketched in Figure 36.

All incoming signals are recorded on the loop which is running continuously. The signal remains on the loop until it completes one cycle through the machine, at which point it is reproduced and fed into a reel-to-reel recorder. When a signal is first received, a relay is actuated which starts the reel-to-reel recorder. The application of the signal to the recorder is delayed by an amount of time equal to one cycle of tape-travel around the loop. This gives the recorder ample time to come up to speed. A time-delay circuit keeps the recorder running for a predetermined interval following the end of the incoming signal. At that

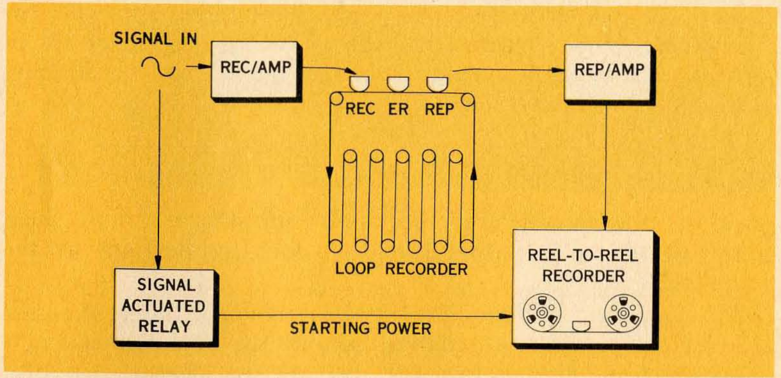


Fig. 36. Tape loop as a time-delay device.

time, it comes to a stop, awaiting the arrival of the next signal. In this way, all significant signal information is recorded on the reel-to-reel machine, and the tape is fully utilized.

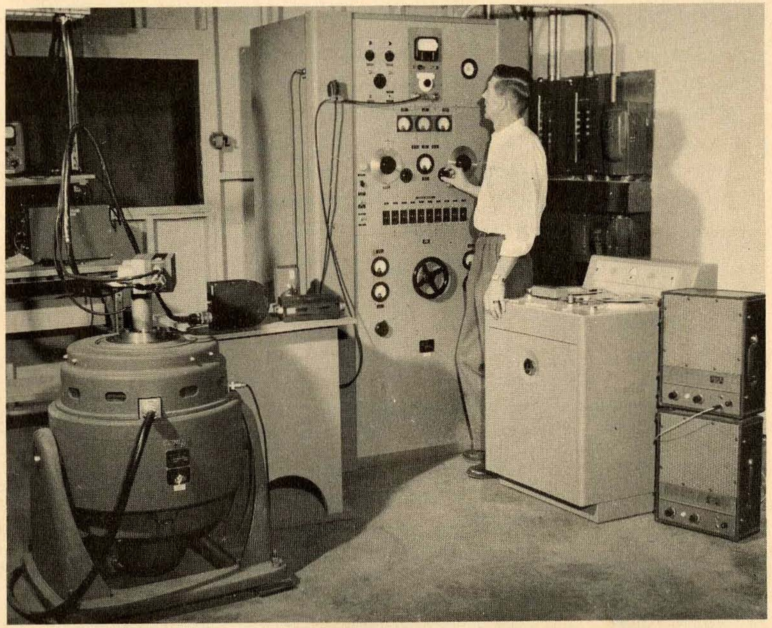
Recreation of Phenomena

There are certain types of tests, events or phenomena of a special nature, from which much valuable data can be collected, but cannot all be assimilated or fully utilized at the time. Examples would be — large-scale or expensive tests, such as an atomic bomb explosion or the destructive test of an engine. The information content of the measurements taken during such events cannot be completely extracted with any reasonable amount of test and measuring equipment at the time and place the test is performed. By recording the measurements on tape, it is possible to recreate the event in the laboratory as often as it is desired — using various analysis equipment and analysis techniques until all of the desired useful information is derived from the measurements.

Programming

Tape recorders provide an excellent means of programming an event, instructions or series of operations for subsequent use in simulation or control. Examples are the following:

(1) *Simulation.* The testing of military components to determine their ability to withstand vibrations expected to be encountered in service have generally been performed on "shake



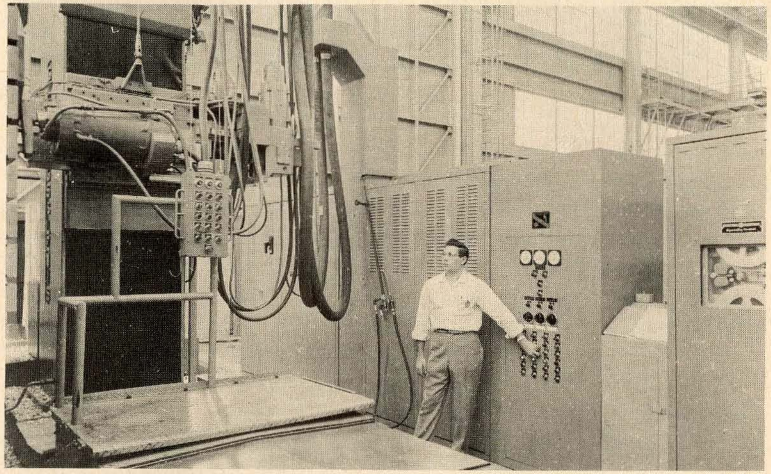
Illust. 21. Magnetic-tape programming a shake table.

tables" which vibrate sinusoidally. It has been found that such tests do not adequately prove out a design, since equipment designed to pass the shake-table tests often fail under actual use. It has been established that the vibrations in military vehicles are generally not of a sinusoidal nature and the usual laboratory recorders have been used to record the actual vibrations encountered in the equipment when mounted on the service vehicle. This recording is then used as the input signal controlling the motion of the shake table—and thereby truly simulating the actual service conditions.

(2) *Machine Tool Control.* Much has been written recently on the use to which magnetic tape has been put in automatically controlling the operation of machine tools. The signal on the tape can be derived from the output of a machine under the control of a skilled operator who is actually making the part. On playback, the recording will then be able to recreate the

original movements of the machine tool and turn out a duplicate of the original part.

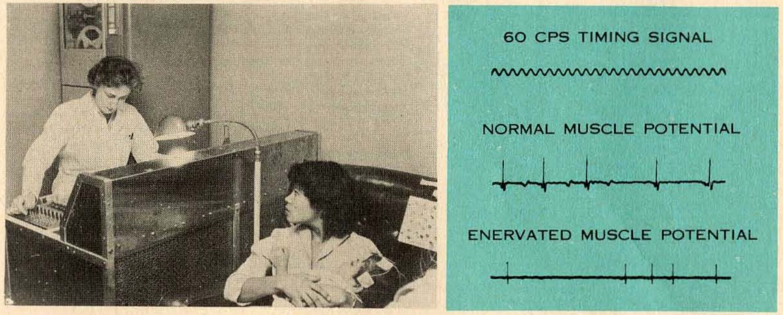
A more advanced approach is the use of a computer to prepare the tape without the need of a machinist performing the original operation. Starting with a blueprint, it is possible to extract sufficient information defining the surfaces of the contours to be generated. This information can be fed into a computer. The computer can translate this information into the correct electrical signals which will then control the various motions of the machine tool and generate the part. It is this output-signal information which can be recorded on a multi-track magnetic tape and reused as many times as desired to turn out quantities of the part. The tape can be duplicated and used with many machines in different places. Consider the impact this new concept has on the logistics of replacement parts, the adaptability to rapid mobilization and the assurance of uniformity in production. These are but a few of the many exciting advantages of magnetic-tape control over machine-tool operations.



Illust. 22. A machine-tool control facility.

(3) *Process Control.* Electrical signals from magnetic tape can operate valves, thermostats, pressure controls, motors, speed controls, or any other desired mechanical or electrical responses. In this way, tape signals in a process sequence can repeat any pattern of temperatures, pressures, agitations, timed feeding of ingredients, etc., that has previously achieved a successful result. Thus, in chemical, metallurgical, manufacturing and similar fields, it is possible to provide precise control over timing and perfect synchronization of all variables.

Magnetic tape can also be used to make a continuous correction in flowing or cycling processes. It can pick up a measurement at one point—be timed exactly with the steady process flow or cycle—then apply a correction at another point some definite time interval later in the process. The tape is used in loop form and is erased and reused each time around.



Illust. 23. Brain-wave recording.

Medical Research

The tape recorder has become an important research tool in the field of medicine. Tape recordings can be made of heart sounds, brain waves, nerve potentials, muscle impulses, and blood flow. The recorded signals can then be analyzed in a number of ways—spectrum analysis, time-base change, graphic plots, auto and cross correlation, and/or by further processing by computers. Extensive libraries of recorded data have already been gathered on normal and abnormal patients, giving much new insight on diseases of the heart, the mind, and the body. From this work, important diagnostic methods are evolving for detecting and identifying these diseases; and it may be expected that new or improved methods of treatment and cure will result.

Automatic Data Processing

In my introductory remarks, I referred to the great need which exists in various test and development programs for making large quantities of measurements and for reducing these measurements rapidly and efficiently. The examples I used were those of the flight test and engine test activities, both of which form so important a part of our present defense program.

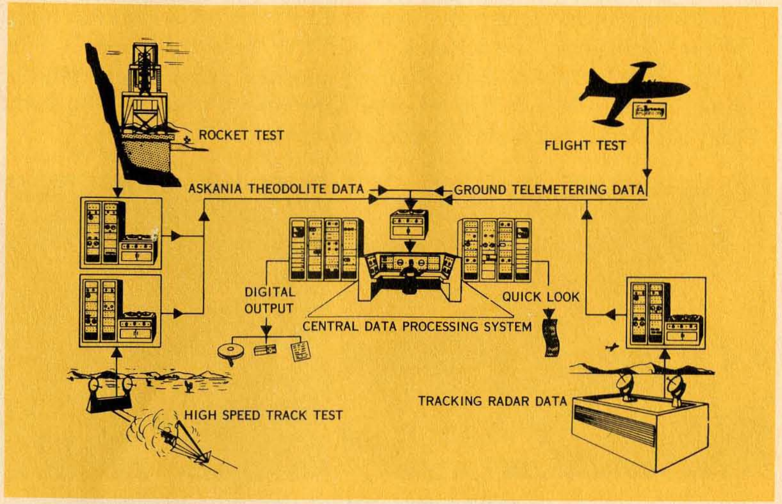


Fig. 37. Data handling systems.

An outstanding example of an activity which has designed and installed a large-scale data-acquisition and automatic data-processing system is the Air Force Flight Test Center at the Edwards Air Force Base in California. Figure 37 illustrates the scope of the data handling system which makes up Project DATUM. It will be noted that magnetic tape is used as the "common denominator," the medium on which all of the primary data is recorded. Some data is tape recorded directly in flight, using airborne recording equipment of the type shown in Illust. 19. Some data is telemetered to the ground where it is tape recorded. The high-speed test track is an example of a test facility using telemetry. Other data, such as that gathered at the Rocket Test Station is recorded directly on the ground.

The Central Data Processing System reduces all of the recorded data from the many sources indicated above. Figure 38 shows this central system in block-diagram form. There are two sections to this system. One, called the *"Quick-Look" section* can reduce the data in the form of pen-and-ink, or oscillographic plots for visual inspection and editing. This data is not calibrated or corrected, but can serve to identify those sections of data which have significant information and warrant further refinement.

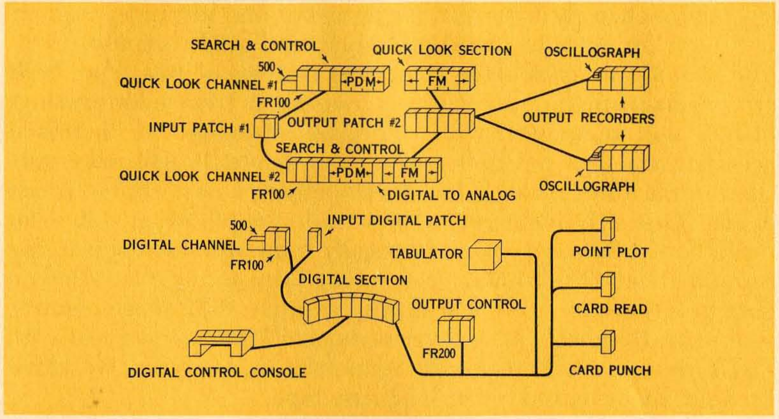


Fig. 38. Project DATUM central data processing system.

A *time code*, which is recorded on all tapes, shows up on the visual record. Thus, the data to be processed further can be identified by its start and stop times. This information is then set into the search and control equipment which can automatically locate a given section of tape (from its start time); play the desired portion; and stop itself at the end (determined by the pre-set stop time). These selected portions of the tape are reproduced on the *digital section* of the Data Processing System. Here, the data is digitized and the following corrections are applied to the data:

(1) Zero, full-scale and sensitivity calibration.
(2) Tape wow and flutter compensation.
(3) System non-linearity correction, including linearization of transducer response.

(4) Scale-factor conversion to produce output in terms of actual physical values (i.e., pounds per square foot, feet, miles, degrees, etc.).

The output of the Central Data Processing System is available in four general forms:

(1) Tabulated data in form for direct use in reports or other analysis without need for further editing or transcribing.
(2) Point-plot graphs of the corrected data.
(3) Magnetic tape in form acceptable by a high-speed digital computer.
(4) Punched cards for further statistical and sorting operations or for entry to a card-programmed digital computer.

The use of automatic data processing systems of this type, built around magnetic-tape recorders, is resulting in tremendous savings in time and manpower, with additional advantages of increased accuracy and less possibility of human errors. It will materially shorten the time cycle in the development of an airframe or jet engine. One airframe manufacturer made the following statement recently. His data system automatically translates into engineering form in about 12 to 24 hours the average one-and-one-half-million data points which are taken during a single B-52 representative test flight. He quotes manpower savings of $200,000 per year with this system, as well as a 50% reduction in computer workload brought about by the use of magnetic tape.

CONCLUSION

I hope this discussion has given you some understanding and appreciation of the magnetic tape recording process; a realization of its advantages as well as its limitations; and an awareness of how tape has been and is being used successfully as a tool for research, design, measurement and control.

I hope I have suggested ways for you to apply this tool to your own projects or programs. It is my further hope that I have excited and stimulated your imagination on the future possibilities of the recording process, as the present limitations are progressively overcome, the frontiers of the art are rolled back and the horizons are broadened.

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