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VIDEOTAPE RECORDING

AMPEX CORPORATION
AUDIO-VIDEO SYSTEMS DIVISION
MAGNETIC TAPE DIVISION

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FOREWORD

The video tape recorders that first went on the air in 1956 were invaluable in their ability to store programs for later release with a picture quality not available with kinescope recording. Nevertheless, the recorders then were extremely simple in comparison with today's machines. Even in the atmosphere of today's high technology, the progress that has taken place in videotape recording is quite remarkable, and may be attributed to three factors. One was the evolution in the field of electronics: transistor technology; integrated circuits and then large-scale integrated circuits, first in digital and next in linear devices; digital signal processing, and microprocessors. The second was the combination of foresight and creativity applied by engineers involved in improvements in the art after 1956, and in user operations as well, in anticipating the need for improved or new capabilities, and bringing them to pass. The third was a significant evolution in the state of the art itself, i.e., a major improvement in the ability to store information on tape and recover it with better quality.

Most of the advances made in the field could be classified either as further development, or as innovation of methods and techniques for meeting new requirements. Neither of the categories predominated over the other in highlights. For example, the high-band standard for video tape recording, which was introduced in the mid 1960s, and to which essentially all video tape recorders in broadcast use were eventually converted, definitely fell into the first group, but was without any doubt a milestone of the greatest importance. It should be noted that the values given in Section 5.2 for carrier frequency and modulating frequency are based on the assumption of the use of the highband standard.

The several-step evolution of electronic editing, described in Section 10, falls into the second category, but has had an impact on the television broadcast and post-production industries as great as any other development or set of developments.

The initial conception and development of electronic time base correction, covered in Section 6, is difficult to assign to either of the categories, but was an essential step toward eliminating geometrical errors, both step-function and continuous, in off-tape pictures, and in eventually being able to recover from tape high-quality color recordings in concurrence with NTSC stipulations.

The multitude of sub-sets in the technology of video tape recording today would make adequate treatment by a single individual quite unlikely. Therefore, contributions were obtained from more than a dozen colleagues, each a recognized authority in his particular speciality.

Portions of the material in this publication were originally submitted to McGraw-Hill for inclusion as Chapter 15 of the 1986 Edition of the Television Engineering Handbook. The Introduction, "The Development of the Videotape Recorder", is taken from a paper delivered at the 82nd Convention of the Society of Motion picture and Television Engineers in Philadelphia, Penn., in Oct. 1957. The original paper was an attempt by the author to give full and accurate credit to each of the members of the original VTR project team, and before its presentation in Philadelphia, was submitted to each of those engineers for criticism and correction. Modifications to the original paper consist of deletions of material that today would be extraneous, and minor changes in wording.

A limitation on space made it necessary to forego completely the discussion on certain subjects, and to minimize the depth of treatment of some others. Conspicious in this respect are the following: a detailed account of the delay of color programs on very early video tape recorders; the color-under technique developed in the early 1970's for accommodating color programs on video tape recorders of restricted bandwidth and limited time base stability; the long and complex history of the development of helical recorders; and the contact duplication of video tape recordings. Nevertheless, we (the contributors) trust that the considerable efforts to produce this work will be found unique and worthwhile.

Charles P. Ginsburg
February, 1986

1. DEVELOPMENT OF THE VIDEOTAPE RECORDER

Charles P. Ginsburg

In October of 1951, after several disputes on the question of how television might be accomplished on magnetic tape, Alexander M. Poniatoff, founder, and at that time president, of Ampex Corporation, and Myron Stolaroff and Walter Selsted, his two top technical aides, agreed that a relatively small sum of money should be appropriated for the purpose of investigating a rotating head approach. The rotating head method was one which had been discussed with Stolaroff by Marvin Camras of Armour Research Foundation, of which Ampex was a licensee. The discussions engaged in by Poniatoff, Stolaroff, and Selsted were concerned with the feasibility of such a system as opposed to other approaches, notably high speed techniques and time division multiplexing schemes. Accordingly, a project was authorized in December of 1951. The opportunity to join Ampex to undertake the project was one that I could not turn down.

Fig. 1 Alexander M. Poniatoff with Early Quadruplex Ampex Videotape Recorder

Prior to the actual start of the project, the conception of the system was merely this. Three heads were to be mounted on the flat surface of a 2-inch wide tape. The head-to-tape speed was to be approximately 2500 ips to allow dependable recording of 2-1/2 megacycle signals, and the tape was to move at 30 ips. The project had a low priority, and in May of 1952 work on the recorder was suspended for three months in favor of a crash project to turn out a one-of-its-kind instrumentation recorder. It turned out to be a fortunate interruption as it puts me into very close contact with a 19 year old student and part-time employee by the name of Ray M. Dolby. Although at that time he had had no formal engineering training, his technical understanding and ingenuity made him a key figure in the development program from the time of his first contact with it. Dolby dropped out of school to join the project when it was resumed in August of 1952 and was rewarded by losing his student draft deferment and being inducted in March of 1953.

In Oct. of '52 we demonstrated a picture that, although barely recognizable, was promising enough to maintain management's enthusiasm. A second system was designed, built, and running in early March of '53. In this, four heads were mounted on the plane face of the drum instead of three in order to make use of a two-way switching system by which during playback the output of either of the two sets of diametrically opposed heads could be selected. The radius of the arc described by the rotating heads was about 1-1/4 inches, permitting approximately 105 degrees of arc to be described by each head as it swept across the 2-inch wide tape.

An amplitude modulation system was used, the video signal establishing the limiting amplitude in a clamp modulator. The capstan motor was driven directly from 60 cycle line frequency and the high speed drum motor by a power amplifier whose input was the fifth harmonic of that signal. A photocell received the reflected light impulses from a light source that was focused on a rotating guard ring. The 300-cycle photocell drive signal was recorded on one edge of the tape by means of a conventional stationary head. During playback, the 300-cycle signal from the tape was used as the input signal to drive and control the drum power amplifier.

Although we were rather pleased by some aspects of our results, we were faced with a number of severe problems. The pitfalls of the discontinuous method of recording were painfully obvious. The label "venetian blind" was used to describe the flaws at the points representing the cross-over from one head to the next in the reproduced picture. The unsuitability of the method of control and the need for extreme accuracy in the positioning of the tape relative to the rotating heads became quite apparent and many hours devoted to analyzing the complexity of potential errors in the arcuate sweep geometry indicated that major revisions would be needed before the rotating head VTR could be successful.

The project was shelved in June of 1953 in favor of a higher priority program, with the understanding that the subject of videotape recording would be revived within a few months in line with proposed solutions to some of the problems.

Between June of 1953 and August of 1954 the videotape recorder had no continuous status, but progress was made on specific problems by means of limited engineering efforts, some authorized and some bootlegged. Backed up by these advances, a report was submitted to management together with an urgent request for an 80-man-hour authorization to modify and demonstrate the recorder, identified by us as Mark I.

Charles E. Anderson and I changed the control system and demonstrated in August for a management committee. As a result, on September 1, 1954, the VTR program recommenced in earnest.

At the outset, there were two major technical changes. The first was a departure from arcuate sweep configuration to the transverse scan geometry, in which the tape was cupped around the rotating drum and the information written across the tape in straight lines. The second was to be the development of an automatic gain control (AGC) system to compensate for all of the continuous as well as the step-function-type of amplitude fluctuations characteristic of the rotating head approach. Late in September, Anderson, Shelby Henderson (our model maker) and I were joined by Fred Pfost and in October by Alex Maxey.

At the beginning of the new project, we had in our possession a total of six individual video heads, four on the old drum and two spares. These heads were the first combination ferrite core and metal tip units made for video recording. They had been constructed a year and a half before, and although quite crude, they had worked at least well enough not to constitute any real limitation in the system performance during the early efforts. Accordingly, in the fall of '54 we were not worried about duplicating the heads. Early attempts to do so were unsuccessful, however, as new video heads continued to fly apart under the high centrifugal force to which they were subjected. The original composite heads were reshaped and used again in the new drum, and it was not until the spring of 1955 that we were finally successful in replacing the old video heads with new ones.

In December of 1954, we made our first picture using the new geometry. The results were gratifying in terms of the improved stability, although the reproduced picture still displayed gross shortcomings. For one thing, the AGC system was not ready for use and it was beginning to be apparent that the problems facing it were extremely difficult.

In late December Anderson proposed using a vestigial sideband FM system rather than the old amplitude modulation. Some technical support to his belief that the new method would work was furnished by results the FFC had obtained a few years earlier in conjunction with tests on vestigial sideband FM transmission of television signals. The big questions for us centered around the very unusual relations among carrier, deviation, and modulating frequencies. Anderson began work on the new system January 2, 1955 and early in February we saw our first FM picture off tape.

Fig. 2 This February 1955 picture from tape convinced Ampex that its efforts were worthwhile. The "venetian blind" effect, seen as horizontal line interference above, was another hurdle to overcome.

Meanwhile, Ray Dolby, who had finished his tour of military service and had returned to Ampex on a part-time basis while continuing a full college program, had started on a simplified FM method. Whereas Anderson had used fairly conventional reactance-tube techniques, heterodyning the sidebands from the 50 megacycle region down to frequencies suitable for reproduction from tape, and subsequently moving the information on playback up to about 50 megacycles for transmission through high frequency IF amplifiers and limiter circuits, Dolby designed and built a multivibrator which could be modulated by applying the composite video signal directly to the control grids.

Since the free-running frequency of the multivibrator could be set to a value suitable for transmission by heads and tape, circuit complexity and development time were greatly reduced. The pictures obtained with the multivibrator on February 25 were even better than those with the reactance tube system earlier in the month.

On March 2, 1955, we gave a very convincing demonstration for the Board of Directors. The resolution was extremely low as the system was somewhat less than 1-1/2 megacycles wide. The monitor had to be operated with a short time constant in the horizontal AFC because of velocity variations in the head drum, which was at that time belt-driven rather than being coupled directly to the shaft of a highly stabilized motor, as was the case later. The month that followed was one of careful deliberation on many questions, all of which had to be answered with reasonable accuracy in order to be able to steer a successful course from breadboard demonstrations to a commercially acceptable product. We proceeded under a new engineering project authorization that stated the objective of having a system for public demonstration within one year.

Fig. 3 By March 1955 the Ampex team had corrected many of the playback problems by introducing an FM signal. The comparative improvement in this picture encouraged Ampex to support the video project with time and money commitments.

In after-hours experiments during February of 1955, Maxey had discovered some very significant phenomena connected with the characteristics of pictures reproduced from tape. He found that the amount of information read out during playback by each of the heads per unit of arc sweep could be controlled by varying the tape tension in any one of three ways: at the reels, by moving the female guide toward or away from the rotating drum, or by varying the vacuum which was pulled from the non-contact side of the tape.

Although we were concerned with the extent of the non-linearities which might be introduced by using the guide position as an information rate control, and did some experimenting with a correction method in which the amount of vacuum was varied, it was determined experimentally that the non-linearity in the first method was quite unobjectionable. This technique of varying the tape tension proved to be one of the major breakthroughs in the program. It provided an excellent solution for the problem of information rate changing as the heads wore down to a smaller sweep radius, and it gave an answer to a part of the question of ultimate interchangeability of recorded tapes from one machine to another.

The entire new head development program was carried by Pfost. He made radical changes in the design of the individual magnetic heads, using a sandwich-type of construction that provided the necessary mechanical support and was highly reproducible as well. The work on heads during this period was done in a much more analytical fashion than there ever had been time for earlier.

The modulation system was extended in bandwidth so that it would be suitable to operate with a carrier frequency of as high as six megacycles if such an operating frequency should subsequently turn out to be usable. The switching unit, which had previously been a two-mode device, was replaced by a four-way switcher that would allow only one channel at a time to conduct. Considerable improvements were made in resolution and in signal-to-noise ratio. The drum was stabilized sufficiently to allow the display of pictures from tape on a standard monitor. No attempt had been made during this period to design the recorder for commercial use. The breadboard consisted of a rather crude wooden cabinet containing the top plate and a few electronic chassis, operating in conjunction with two partially full racks. At a demonstration given for some officers of the firm toward the end of 1955, it was suggested that we should package more attractively what was going to be a very expensive recorder. Accordingly, Anderson designed the Mark IV console with its compact rack arrangement. It was also decided at this time that plans should be directed towards a surprise demonstration at the National Association of Radio and Television Broadcasters convention in Chicago in April of '56.

In early February of 1956, a demonstration was given for what was originally supposed to be a very small management group but turned out to be attended by about 30 Ampex people. For all of us on the engineering project, this was the most dramatic demonstration. The guests arrived, were seated, a few words were spoken to the effect that they would see the results of the work to date, and the recorder was then put in the playback mode and played back a program recorded an hour earlier.

It was then announced that a sequence would be recorded and immediately played back. We recorded for about two minutes, rewound and stopped the tape, and pushed the playback button. Completely silent up to this point, the entire group rose to its feet and shook the building with hand-clapping and shouting.

Fig. 4 When good picture quality became a matter of routine, the Ampex team was ready to show videotape recording to the world.

We had quite a few visitors during the next couple of weeks, including Bill Lodge of CBS, Frank Marx of ABC and representatives of the CBC and BBC. The visitors were all sworn to secrecy and ushered in and out separately so that they would not see each other. As a result of Lodge's visit, arrangements were made to use the Mark IV model, which had not yet been assembled, for a surprise showing to the annual CBS affiliates meeting that was to occur the day before the formal opening of the NARTB convention.

With about six weeks left before the convention, working hours were extended to complete the construction of Mark IV and at the same time to continue development work so that the picture to be demonstrated in Chicago would be as good as CBS was expecting it to be. The activity became furious. The administrative engineer for the group, which by now numbered about a dozen people, spent most of his regular time plus nights and weekends modifying mounting brackets for the Mark IV console, making cable assemblies, and building up redesigned electronic units.

A three year old idea of placing the switching transients in the horizontal blanking interval was rushed into hardware form as the blanking switcher, and integrated into the basic system as a toggle-switch option. An automatic rotary head degaussing system was devised to eliminate the need to manually demagnetize the video heads after a recording operation and prior to playback.

Meanwhile it had been decided that Mark III, the machine used for the prior demonstrations in February, should be used for a press demonstration in Redwood City, California, on the same day that the NARTB showing was to start. Therefore, while Mark III was being used for development work, barely leading the construction of Mark IV, it also had to be prepared for its press appearance.

At last Mark IV was completed, debugged, and then broken down into many pieces and shipped to Chicago. Three days before the press demonstration, Mark III was in severe trouble. Those of us who were headed for Chicago took off, wishing the stay-at-homes good luck and trying not to think about their difficulties.

The demonstrations were scheduled for Saturday. By Thursday afternoon, Mark IV was assembled in Chicago and making the best pictures we had ever seen from tape. A predictable situation then occurred. The CBS engineering staff said the pictures were not good enough. The signal-to-noise ratio was too low and the noise banding was intolerable.

Between Thursday night and Friday night, we made it. By cutting, trimming and adjusting and aided by the last minute delivery of some tape samples that greatly exceeded in performance anything we had seen before, everyone was satisfied. Checking with the crew in Redwood City, we found that they had solved their mechanical problems and were now ready for the demonstration.

The demonstrations were a bomb shell in the industry. In Redwood City the performance was sensational. In Chicago, pandemonium broke loose and Ampex was flooded with orders. From the time of the CBS affiliates meeting on Saturday morning, through the demonstrations extending until the following Thursday afternoon for the convention delegates in general, the recorder performed better than we had any right to expect.

The next several months were just hard work. Four months earlier Ampex had expected to deliver five prototype VTRs, beginning in late Summer or early Fall, to customers in government agencies, for evaluation, along with a program leading to gradual delivery of machines for TV use starting in 1957. Now we were faced with the pressure of making 16 hand-built machines, most of them going to broadcasters for immediate on-the-air use, and at the same time we had to gear up for full-scale production of units the industry was eager to put to work.

In spite of the subjectively good pictures demonstrated in April of 1956, a resume of the tasks that had to be covered before releasing the first machine for air use reveals how shaky our ground actually was at the time. Until then, neither manpower nor machine facilities nor technical advances were sufficient to properly evaluate magnetic tape for videotape recording use. And until means could be devised to rate the tape manufacturers' samples with quantitative evaluations rather than with such subjective appraisals as "too many dropouts", or "doesn't wear well", not too much could be accomplished toward getting really satisfactory tape.

The tape evaluation program consumed many hundreds of man hours and was the cause of severe headaches to the tape manufacturers, to us, and to our early network customers. With a then-predicted head life of 100 hours, we could not continue to make heads in a tedious one-at-a time fashion. The many parameters in head construction, several of which had been varied in cut-and-try fashion in order to squeeze out a few more dB of signal for the April demonstrations, had to be fixed in order to establish our own standards before the delivery of the first machines.

At the same time, head construction had to evolve into a semi-production process rather than a handcrafting technique. A processing unit had to be designed and developed which would be capable of providing blanking and sync in the reproduced signal that were sufficiently free of noise to allow the signal to be handled without difficulty by conventional stabilizing amplifiers and clamps anywhere along the line of transmission. The picture reproduced from tape had to be greatly improved over that shown in April with respect to noise, resolution, overshoot and ringing, and horizontal stability. The entire machine and all individual chassis had to be repackaged and tested. The mechanical design details were endless. Our top plate components had to be not only reliable but completely interchangeable. And always the struggle for greater bandwidth and better signal-to-noise ratio. The length of work days peaked in October and November, and many times during this period a crew of two or three engineers would start a day at eight in the morning and finish it 30 hours later.

Fig. 5 The historic first broadcast via tape was CBS' November 30, 1956 airing of the "Douglas Edwards and the News" program from New York City. CBS Television City in Hollywood, pictured above, replayed the broadcast three hours later on the West Coast and in the months following, the other networks were to follow CBS's lead.

Fig. 6 The six-man team that developed the first practical videotape recorder gather around the results of their labors, the Ampex Mark III, with the Emmy Award won by Ampex in 1957. They are, left to right, Charles E. Anderson, Ray Dolby, Alex Maxey, Shelby Henderson, Charles Ginsburg, and Fred Pfost.

The videotape recorder went on the air for the first time on November 30, 1956, from CBS Television City in Los Angeles. NBC followed suit at the very beginning of 1957, and ABC started delayed telecasts from tape at the beginning of daylight savings time in April.

2. FUNDAMENTALS OF MAGNETIC TAPE RECORDING

Beverley R. Gooch, H. Neal Bertram

2.1 FUNDAMENTAL RECORD AND REPRODUCE PROCESS (Gooch) The modern magnetic tape recorder represents a highly developed technology, the result of many innovations and refinements since its invention by Valdemar Poulsen in 1898. Today many technologies depend on the magnetic recorder in one form or another as an information storage device. The advancements in recording media, heads and signal processing techniques, have made it possible to achieve packing densities that rival or exceed most other information storage systems.

Magnetic recording is basically a moving medium information storage process, which requires a means to transport the medium, usually at a constant velocity, past the record and reproduce heads. To achieve the necessary bandwidth for video recording, the heads are rotated at a relatively high velocity with respect to the tape, and a series of narrow tracks is recorded sequentially.

The basic elements of a magnetic tape recorder are shown diagramatically by Fig. 7. A magnetic tape is moved in the direction indicated by a *tape drive device* or *transport*. The magnetic coating of the tape contacts the magnetic heads in a prescribed sequence, starting with the erase head and ending with the reproduce head.

The erase head (not shown) demagnetizes the tape coating by exposing the magnetic particles to a high frequency field that is several times greater in strength than the coercivity of the particles. As the tape is drawn past the erase head, the erasing field gradually decays, leaving the magnetic coating in a demagnetized state.

The tape then moves into contact with the record head, which consists of a ring-shaped core made of a relatively high permeability material, and having a non-magnetic gap. A magnetic field fringes from the gap, varying in accordance with the magnitude of the current signal flowing in the head coil. With low level signals the field is small, and some magnetic particles in the tape coating will be forced into alignment with the field. As the signal field is increased, a larger number of particles will become oriented in the direction of the recording field. As the tape is moved past the record gap, the magnetic coating acquires a net surface magnetization having both magnitude and direction. This magnetization is a function of the recording field at the instant the tape leaves the *recording zone*, a small region in the vicinity of the trailing edge of the gap.

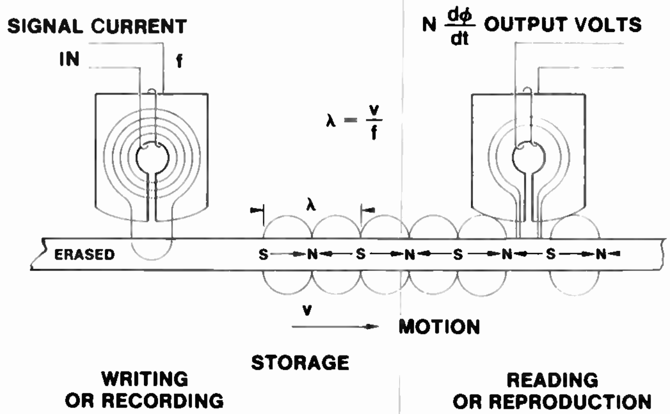


Fig. 7 Fundamental Recording and Reproduction Process

The magnetization of the fundamental record system just described is not necessarily linear with respect to the head current. Linear magnetization can be achieved by adding a high frequency ac bias current to the signal current. Audio recorders use such a scheme to linearize the tape and reduce the distortion. In video recorders, the signal information in the form of a frequency modulated carrier is recorded directly, without ac bias.

When the tape approaches the non-magnetic gap of the reproduce head, the flux from the magnetized particles is forced to travel through the high permeability core to link the signal windings and produce an output voltage. The output voltage is proportional to $d\Phi/dt$, the rate of change of the inducted flux, and therefore will rise at the rate of 6 dB per octave until a wavelength is reached where the gap and spacing losses begin to reduce the head output. These effects will be discussed in detail in the following section.

Wavelength of the Recorded Signal The physical distance that one cycle of the recorded signal occupies along the tape is the *wavelength.* It is directly proportional to the relative velocity v between the head and the tape, inversely proportional to the frequency of the recorded signal. Thus,

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

where λ is the wavelength in inches, and v is the velocity in inches per second, f is the frequency in Hz.

Linear Packing Density: The linear packing density is the number of flux reversals per unit length along the recording medium. As there are two flux reversals, or bits, per cycle, the linear packing density may be expressed as:

$$\text{bits/in} = 2\left(\frac{1}{\lambda}\right) = \frac{2}{\lambda}$$

where λ is in inches

Area Packing Density: The area packing density is the number of bits per unit area, and is therefore equal to the number of recorded tracks per inch times the linear packing density, or

$$\text{bits/in}^2 = \left(\frac{2}{\lambda}\right) \text{tracks/in}$$

Table I compares the linear packing density and the shortest recorded wavelength of various types of magnetic recorders.

Table 1 High and Medium Density Recording Applications

HIGH DENSITY

Recorder	Tape Speed	Maximum Frequency	Minimum Wavelength	Linear Packing Density
Quadruplex Video	1500 IPS	15 MHz	100 μIN	20,000 BPI
Type C	1000 IPS	15 MHz	70 μIN	30,000 BPI
Consumer Video	220 IPS	7 MHz	30 μIN	64,000 BPI
Instrumentation	1-120 IPS	2 MHz	60 μIN	33,000 BPI
Audio Cassette	1 7/8 IPS	20 kHz	94 μIN	21,300 BPI

MEDIUM DENSITY

Recorder	Tape Speed	Maximum Frequency	Minimum Wavelength	Linear Packing Density
Professional Audio	15-30 IPS	20 kHz	750 μIN	2700 BPI
Computer Tape	45 IPS	36 kHz	1.25 MILS	1600 BPI
Computer Disc	1000 IPS 1000 IPS	4.5 MHz 4.5 MHz	222 μIN 222 μIN	9000 BPI 9000 BPI

Directions of Recorded Magnetization: When the magnetization is oriented in the direction of relative motion between the head and tape, the process is referred to as *longitudinal recording*. If the magnetization is aligned perpendicular to the surface of the tape, it is called *vertical* or *perpendicular* recording.

Transverse recording exists when the magnetization and the head gap are oriented at right angles to the direction of relative head-to-tape motion. From these definitions, longitudinal magnetization patterns are produced by both rotary and stationary head recorders. Therefore, stationary head recorders should be referred to as such and not called longitudinal recorders.

2.2 RECORDING PROCESS (Bertram)

Saturation Recording The recording process consists of applying a temporally changing signal voltage to a record head as the tape is drawn by. The magnetic field which results from the energized head records a magnetization pattern which spatially approximates the voltage waveform. In saturation or direct recording the signal consists of polarity changes with modulated transition times or *zero crossings*. Strict linear replication of this signal is not required since the information to be recovered depends only on a knowledge of when the polarity transitions occur. Examples are *digital recording*, where the transitions are synchronized with a bit time interval and occur at bit positions depending upon the coded pattern, and *FM video recording*, where a modulated sinewave is applied so that the transitions occur not regularly but according to the signal information contained in the modulation.

The essential process in direct recording is therefore the writing of a transition or polarity change of magnetization. In Fig. 8 the resulting magnetization from a step change in head voltage is shown. In saturation recording the spatial variation of magnetization will not be a perfect replica of the time variation of signal voltage. Even if the head field change is perfectly abrupt the magnetization will gradually change from one polarity to another. In Fig. 8 this is indicated by a gradual change in vector lengths; the notation a_t denotes an estimate of the distance along tape over which the magnetization reverses. The non-zero distance between polarity changes of magnetization is due to the finite loop slope at the coercivity combined with the gradual decrease of the head field away from gap center. This process is illustrated in Figs. 9 & 10.

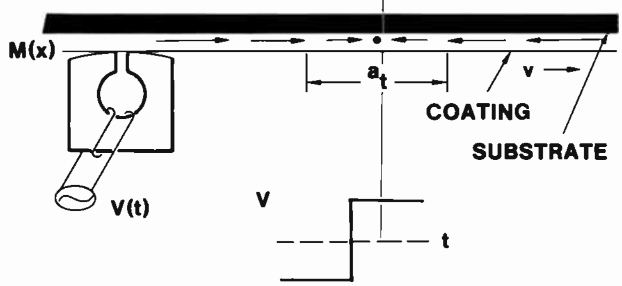


Fig. 8 Resultant Magnetization From a Step Change in Head Voltage

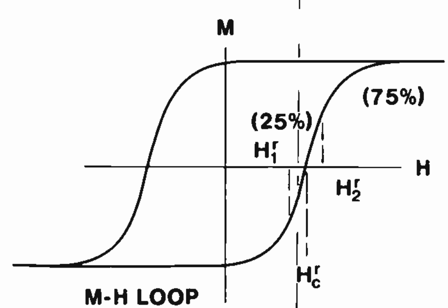


Fig. 9 M-H Hysteresis Loop for a Typical Tape

In Fig. 9, the M-H remanence loop is shown for a well oriented tape sample. The magnetization M is the remanence magnetization which results from the application of a field H which is subsequently removed. If the tape is saturated in one direction, for example -M, and a positive field is applied, then the magnetization will start to switch towards the positive direction when the field is close to the remanent coercivity H_c^r. Since the slope of this M-H loop is not infinitely steep for fields near H_c^r, the switching will take place gradually. H_1 denotes the field which switches 25% of the particles to leave the magnetization at $-M/2$; H_c^r is, in fact, the 50% reversing field which leaves $M=0$. H_2 denotes the 75%

switching field that leaves the magnetization half way to positive saturation ($+M/2$). During recording a finite transition width will occur, depending on how H_1 & H_2 are spatially separated.

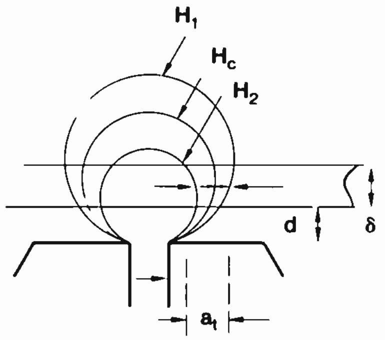


Fig. 10 Head Field contours Showing Recording Zone in Tape

Three contours of recording field are plotted in Fig. 10 for the three fields H_1, H_c^r, H_2. In plots of head fields, larger fields are closer to the surface of the head and towards the gap center. Along the midplane of the tape the field magnitudes H_2, H_c^r, H_1 are in decreasing order away from the gap centerline. If the tape is initially magnetized negatively, a positively energized head (Ho) will switch the magnetization according to Fig. 9, following the spatial change of the fields. This yields a finite transition width a_t. The transition width can be narrowed by using tape with a steeper loop gradient making H_1 closer to H_2 in magnitude (a narrower spread in switching fields) and decreasing the head-to-tape spacing which moves H_1 & H_2 closer together spatially (a larger head field gradient) as indicated in Fig. 10. In addition, spatial changes in magnetization cause demagnetization fields in the tape which further broaden the transition. The demagnetization broadening may be reduced by increasing the tape coercivity. The physics of this process may be seen in the calculation of the transition width, a_t, by Williams and Comstock for thin media [1]. As the following section will show, a large transition width reduces the short wavelength output and broadens the isolated voltage pulse.

In saturation recording the signal current is held fixed for all wavelengths. The current level is set to optimize the short wavelength output and complete saturation of the tape does not occur. Reproduce voltage vs input current is shown in Fig. 11 for two different wavelengths, in square wave recording on Ampex 196 video tape. If true saturation were to occur the curves would increase initially with current as the tape is recorded, and then level, representing a magnetization saturated to full remanence and recorded fully through the tape thickness (200μ" for 196). However, at short wavelengths these curves are peaked, and the current which yields the maximum output represents recording only a very small distance into the tape. For video recording on a Type C format machine optimized at 10 MHz ($\lambda \approx 100\mu$"), the record depth is approximately 50 μ". For a VHS cassette recorder optimized at 30 μ" wavelength, only 20 μ" of the surface layers is recorded under optimum conditions. A mechanism for this optimum can be seen by considering the change in transition with record current. As the current is raised, the point of recording shifts continuously downstream from the gap center. The transition width depends upon the head field gradient at the recording point. This field derivative, $H_2 - H_1$ divided by the separation between them, increases with distance along the head surface, as shown in Fig. 10, reaching a maximum near the gap edge and thereafter decreasing. Since the reproduce voltage increases with decreasing transition width, a maximum voltage will occur as the current is increased. From the reproduce expression discussed in Sec. 2.2, it is evident that this peaking becomes more pronounced as the wavelength is reduced.

A form of linearity known as *linear superposition* is found in saturation recording. For constant current recording (strictly, *constant field amplitude)* the reproduce voltage from a complicated pattern can be shown to closely resemble the linear superposition of isolated transition voltage pulses, according to the timing and polarity change of the series of transitions. The lack of complete linear superposition is believed due to demagnetization fields. This accompanies large head-to-medium separations, as in rigid disk applications, where the increase in the demagnetization fields can cause significant non-linearities.

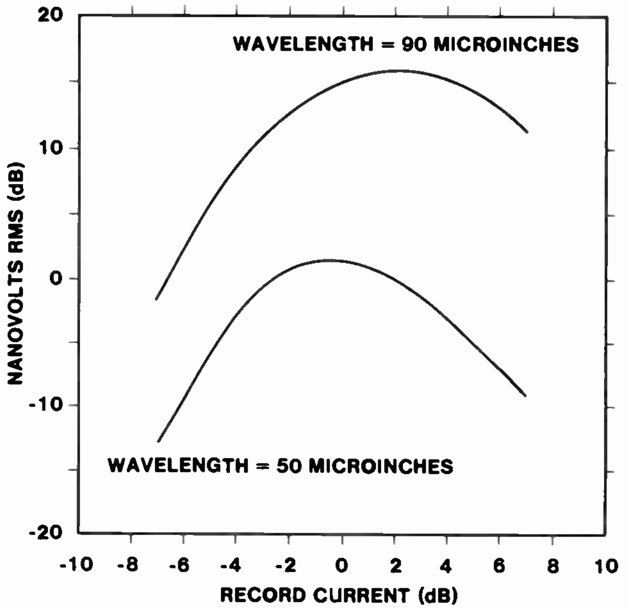


Fig. 11 Reproduce Voltage vs Record Current for Typical Video Tape

Bias Recording In some applications, predominantly audio recording, strict linearity is required between the reproduced voltage and the input signal. This may be achieved by superimposing a high frequency, large amplitude bias current on the signal (Fig. 12). The physical process is called *anhysteresis* [2]. The bias field supplies the energy to switch the particles while the resulting remanent magnetization is a balance between the signal field and the interparticle magnetization interactions. A comparison is shown in Fig. 13 between the magnetic sensitivity of ac bias recording and direct recording. Ac bias or anhysteresis results in an extremely linear characteristic with a sensitivity an order of magnitude greater than that for unbiased recording. In typical audio applications the bias current is somewhat greater than that of the signal in direct recording. The signal current is approximately an order of magnitude less than the bias current and is set to maintain the harmonic distortion below 1 to 2%. For complete anhysteresis there should be many field reversals as the tape passes the recording point where the bias field equals the tape coercivity. This is achieved if the bias wavelength is substantially less than the record gap length. In fact, to avoid reproducing the bias signal itself, the bias wavelength is usually less than the reproduce gap length.

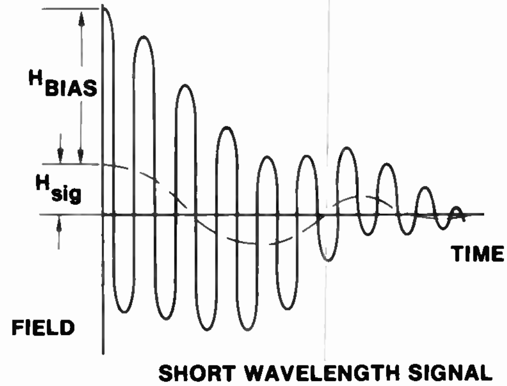


Fig. 12 Signal Field History for a.c. Bias and Recording

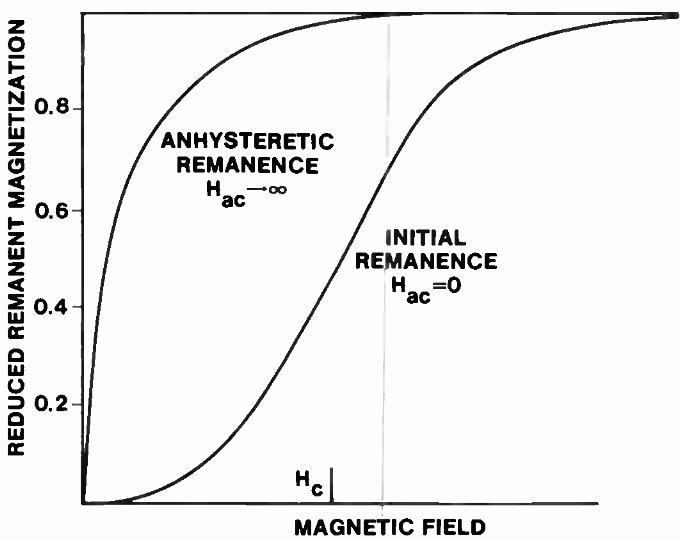


Fig. 13 Comparison of Sensitivities of a.c. Bias and Direct Recording

As in direct recording, a current optimization occurs, but in bias recording it is with respect to the bias current. In Fig. 14, reproduce voltage is shown vs bias at short and long wavelengths. At long wavelengths the optimum (LWBO) occurs approximately when the bias field has recorded through to the back of the medium. This is often taken to be the usable bias current since close to this optimization a minimum in the distortion occurs. For shorter wavelength machines, such as audio cassettes, the bias is chosen as a compromise between short-wavelength bias optimization (SWBO) and long-wavelength bias optimization (LWBO).

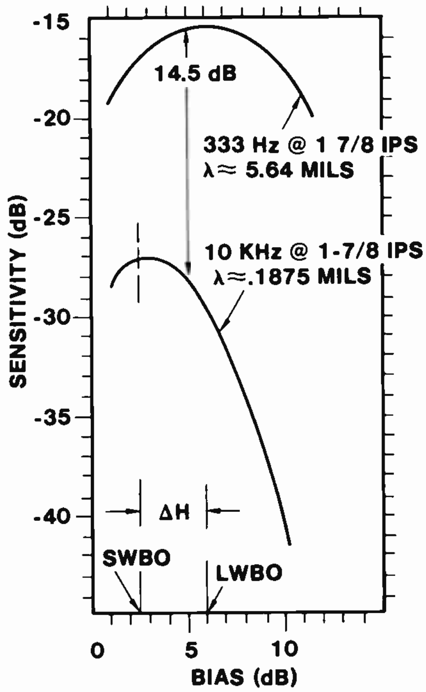


Fig. 14 Low Level Output Sensitivity of a.c. Bias for a Long and Short Audio Cassette

Particle Orientation The previous discussion applies generally to all types of recording tape; the most common is that composed of uniaxial elliptical particles oriented *longitudinally* in the direction of head-tape motion. However, *isotropic* tape does exist composed of particles of cubic (four-fold) symmetry which exhibit high remanences in all directions. In addition, it is conceptually possible to *vertically* orient the grains to result in a tape isotropic in the plane but capable of recording signals perpendicular to the surface. These last two would be advantageous for transverse recording since the difficult process of orienting elliptical particles along the tape cross-direction could be avoided.

During the tape coating process elliptical particles will naturally orient along the tape coating direction. A field applied during coating improves the orientation even further. It is extremely difficult to orient these particles vertically since the hydroscopic coating forces overwhelm the magnetic force from a vertical orienting field. Thus, the only success has been with systems that *inherently* yield vertical orientation. As an example, barium ferrite platelets have been successfully coated to yield perpendicular media, since the magnetization anisotropy axis is perpendicular to the plane of the particles. To date, one other vertical medium has been made by sputtering CoCr on either tape substrate or a rigid disk.

Sufficient experimental comparisons or theoretical analyses have not yet been performed to compare the performance of various particle orientations. However, with regard to contact recording on tape composed of individual particles, it appears that vertical or isotropic media may record larger short wavelength signals than longitudinally oriented tape [3]. The reason is that at the surface of a recording head the fields are primarily vertical, and it is the surface magnetization which dominates the short wavelength signal. For media with large magnetizations such as the vertically oriented cobalt chromium or thin planar cobalt nickel metallic films on tape or rigid disc the performances seem comparable [4]. Both of these high magnetization media are superior to conventional oxide media.

Erasure The writing of new information on previously recorded media requires that the previous information be adequately attenuated. Erasure requirements in terms of previous-signal-to-new-signal ratio vary from -30 dB for digital systems to as much as -90 dB for professional audio. Video recorders require about -60 dB. Erasure is the ac bias, or anhysteretic process with zero signal field. If a reel of tape is placed in a large ac field which is slowly reduced so that many field cycles occur when the field is near the coercivity, then complete erasure is easily obtained. In addition, the largest amplitude of the ac erasing field must be sufficient to reverse at least 99.9% of the particles (for -60 dB), and in practice that field is about three times the coercivity.

Most tape recorders utilize erase heads to remove old information before recording new data. Similar to bias recording, the requirement of the erase frequency is that the wavelength be much less than the erase head gap to provide sufficient reversals of the particles. However, one important problem occurs with an erase head. As the erase current increases, the erasure does not continue to increase as more of the MH loop tail is switched. There is an erasure plateau of about -40 dB for erase gap lengths of 1-2 mils and tape thicknesses of 200-400μ". This leveling is believed to be due to the phenomenon of re-recording [5]. As the tape passes the erase head the field from the portion yet to be erased (entering the gap region) acts as a signal for the bias-erase field to record a residual signal at the recording zone on the far side of the gap. This effect is only seen at long wavelengths where the field is significant. The problem is eliminated with double erasure by using a double gap erase head. The erasure may be increased by decreasing the ratio of the tape thickness (or recording depth) to erase-gap-length; this reduces the re-recording field.

2.3 REPRODUCE PROCESS (Bertram)

In the previous section the process of writing magnetic information on tape was described. Here the reproduction of a recorded signal will be described in terms of the spectrum of a recorded squarewave. A squarewave of record current is assumed, resulting in a magnetization pattern of alternating polarity of fundamental wavelength λ. Each transition of magnetization is taken to be arctangent in shape with a transition width a_t and saturation magnetization M_r (Fig. 8). The mathematical form is $M(x)=\frac{2}{\pi} M_r \tan^{-1}(x/a_t)$. The magnetization pattern is assumed to be invariant with depth in both magnitude and direction. The direction can be at any angle, from longitudinal to vertical, since orientation yields only a constant phase shift which amplitude spectra will not show. Viewing Fig. 15 (Intro), as the recorded tape passes the head, the external fields or flux due to the spatially varying magnetization pattern enter and circulate through the highly permeable reproduce head. The flux changes with time as the tape moves past the record head giving a reproduce voltage. This voltage may be expressed as

$$V=\frac{4}{\pi} NW\epsilon v\mu_o M_r \frac{2\pi d_c}{\lambda} \cdot \frac{\left(1-e^{-2\pi d_c/\lambda}\right)}{2\pi d_c/\lambda} \cdot e^{-2\pi(a+a_t)/\lambda} \cdot \frac{\sin 1.11\pi g}{1.11\pi g/\lambda} \qquad (2)$$

where

N = no. of reproduce head turns
W = trackwidth
ϵ = reproduce head efficiency
v = head to tape relative speed
μ_o = permeability of free space = $4\pi\times10^{-7}$ H/M
M_r = tape remanent magnetization
d_c = depth of recording
λ = wavelength
a = head to tape spacing
a_t = recorded transition width
g = reproduce gap length

The voltage is the fundamental component of wavelength λ. This expression may be separated into various terms which relate to different physical effects. The first terms $\left(\frac{4}{\pi} NW\epsilon v\mu_o M_r\right)$ are the calibration constants. $4/\pi$ is the amplitude of the fundamental of a squarewave. N,W,ϵ,v are respectively the number of turns of the reproduce head, the reproduce track width, the head efficiency, and the head-to-tape relative velocity. μ_o is the permeability of free space $(4\pi\times10^{-7}H/m)$. M_r is the remanent magnetization. The voltage may be evaluated using metric (mks) units for these constants. The subsequent terms in Eqn. 1 depend on length ratios only, so the dimension chosen is not critical. A convenient working relation is that the *rms* voltage in nanovolts per turn per width of track (in mils) per unit efficiency per speed (in in/sec) is approximately $M_r/16$ times the other factors. Here M_r is in gauss. As an example the maximum voltage for a 196 video tape on a Type-C format VTR is evaluated. In that case N = 6, W = 5 mils, v = 1000 ips, $\epsilon\approx0.8$, M_r ~1100G. Then the reproduce spectral voltage constant is

$$\frac{6.75 nV\ rms}{turns \cdot mils\ of\ tracks\ width \cdot \epsilon} \; (M_r/16)$$

or approximately 1.65 millivolts. Measured voltages are a factor of 5-10 less than 1.65

millivolts; primarily, this is due to other factors in Eqn. 1 which are discussed next.

Reference to Fig. 16 will help in the discussion of the wavelength dependent factors. This is a plot of the spectrum of 196 video tape using a conventional Type-C format head with a gap of 35μ". In this experiment the current was set before the spectral sweep to a value which maximized the shortest utilized wavelength ($\lambda = 60\mu$"). The output from the reproduce head was amplified by a flat amplifier; no pre or postequalization was used. Over the frequency range measured, the head losses were minimal, so the head efficiency was constant with frequency. Thus the shape of the spectrum represents the wavelength dependent factors in Eqn. (1). The term $2\pi d_c/\lambda$ in equation (1) represents the head differentiation of the flux and varies linearly with frequency. In Fig. 16 this is the initial 6 dB/octave rise at low frequencies (curved on a log-linear plot). The recorder does not reproduce d.c. - only temporal changes in flux yield voltage for a conventional reproduce head. If this were the only factor the voltage would continue to rise at 6 dB/octave indefinitely. The term $\frac{(1-e^{-2\pi d_c/\lambda})}{2\pi d_c/\lambda}$ gives the first limiting factor to that rise, i.e., the *thickness loss*. As Fig. 16 indicates, this term causes the spectrum to level. The reason is that the reproduce head only senses wavelength components which are approximately one-third of a wavelength ($\lambda/3$) of the coating surface. Thus, as the wavelength is shortened below about three times the recording depth ($3d_c$), the reproduce process senses increasingly less of the recorded layer. The combination of the increase in voltage due to differentiation and the decrease due to the restricted sensing depth balance to give a constant voltage.

The next term $e^{-2\pi(a+a_t)/\lambda}$ is the spacing loss which causes a decrease in the output with increasing frequency. This effect is physically the same as the thickness loss term since that term, arose from the head not sensing the far layers of the recording. The exponential spacing loss plotted log linear, is a straight line equal to 54.6 $(a+a_t)/\lambda$. As the frequency is increased the level response is reduced linearly with slope $a+a_t$. The actual head to tape spacing is a, and a_t is the transition width discussed in the previous section. The transition width enters the reproduce voltage spectrum as an effective spacing. In fact, from Fig. 16, $a+a_t$ from the data is approximately 15μ". Since the data is for contact recording, the measured slope must be due primarily to the width of the recorded transition. The terms discussed so far involve only tape parameters (a, d_c, a_t). The term $\sin(1.11\pi g/\lambda)/(1.11\pi g/\lambda)$ is the gap loss which is the primary head geometric effect. g is the gap length of the reproduce wavelength. As the wavelength approaches the gap length the flux is shunted across the gap and, at a wavelength of $\lambda=1.11g$, there is a null in the output. The data (dashed curve) in Fig. 16 has been corrected for this factor in order to clearly exhibit the spacing loss term; the solid curve includes the gap loss term as measured. After the first null at $\lambda=1.11g$, the spectra rises and peaks before decreasing to the second null and so on according to the $\frac{\sin x}{x}$ function. The figure shows that the response of a recording channel is bounded between dc ($\lambda=\infty$) and the first gap null ($\lambda=1.11g$). A practical channel which would not invoke excessive equalization would be limited to an upper frequency or shortest wavelength of about twice the gap length. The lower frequency or largest wavelength would be limited by the decrease of the spectrum to zero at dc which occurs at a wavelength about an order of magnitude larger than the recording depth. For the video example shown in Fig. 16, a practical channel would cover the wavelength range from 400 μ" to 60 μ" or, at 1000 ips relative speed, frequencies from 2.5-15 MHz. This spectrum also applies approximately to bias recording where M_r is replaced by the signal field (H_{sig}) times the anhysteretic susceptibility [6].

There are additional reproduce phenomena which affect the spectral shape. Three are discussed here:

a) Azimuth loss

The azimuth loss occurs if the reproduce head is rotated with respect to the recording phase fronts of the original

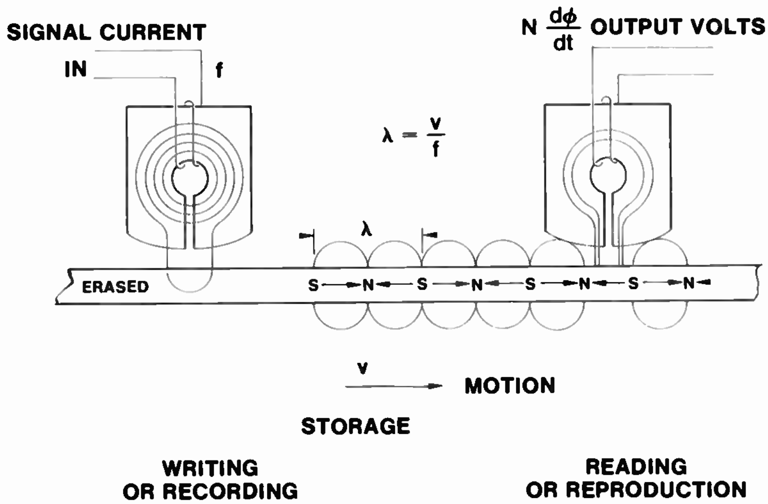


Fig. 15 Fundamental Recording and Reproducing Process

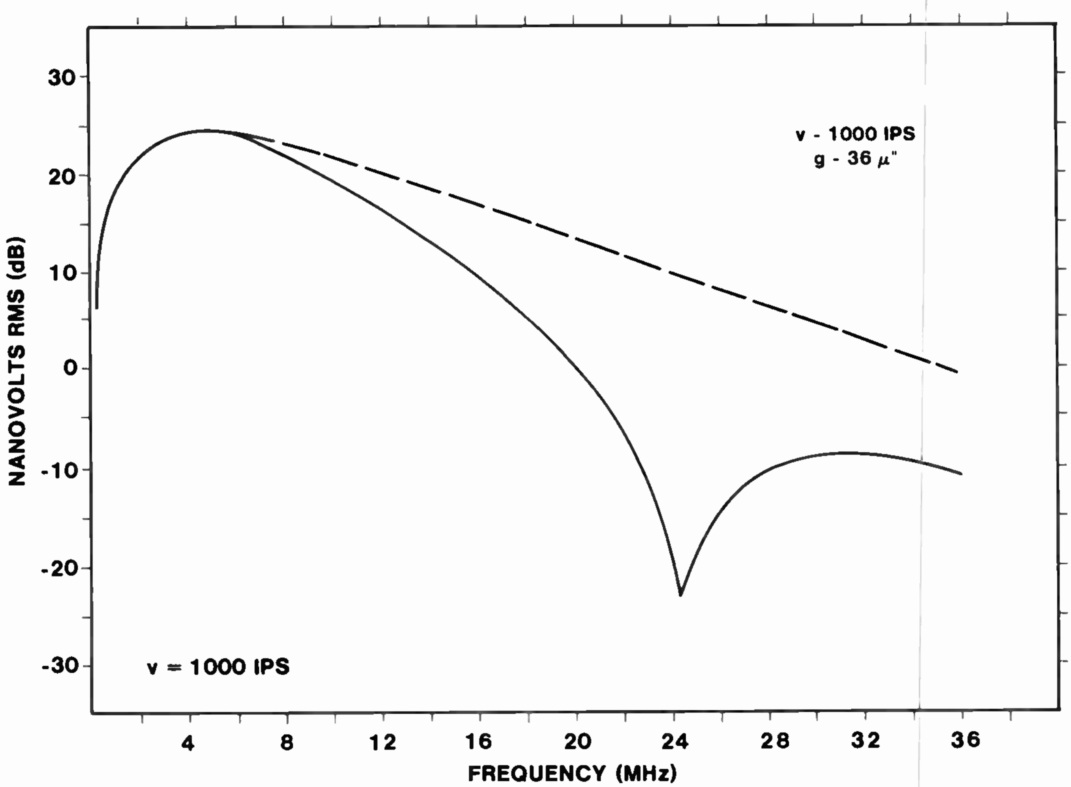


Fig. 16 Voltage Spectrum for Typical Video Tape

recording. In Fig. 17 a reproduce head is shown angled at an angle θ with respect to the original recording. This rotation causes the signal to be reproduced at different times across the track. This continuous phase shift across the track causes an additional loss of the form:

$$\frac{\sin\left[(\pi W \tan\theta)/\lambda\right]}{(\pi W \tan\theta)/\lambda}$$

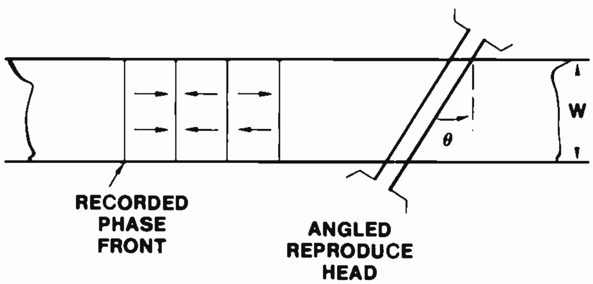


Fig. 17 Azimuth Misalignment Geometry

This loss can easily be severe, since for a video recorder with W = 5 mils and $\lambda=100\mu$", a 4 dB loss occurs for a value of only 3.3 minutes of arc!. Dual headed machines have an azimuth alignment adjustment. Even machines which use the same head for record and reproduce, where theoretically this loss should not occur, may show this effect as a random fluctuation due to tape stretching during play.

b) Head Length Loss

When the wavelength of recording lengthens to approach the length of the reproduce head or longitudinal distance of head-to-medium contact, undulations in the response will occur. At these wavelengths the flux can partially return through the air to the tape and not enclose the windings. For certain conditions a flux reinforcement can occur to raise the level above that given in Fig. 16. This effect is strongest with sharp 90° head edges. Rounded corners softens the undulations and in fact a head with a circular shape shows no undulations [7]. It is desirable to choose a contour which removes the undulations, since they are hard to equalize, and cause phase shift. A theoretical discussion of the undulations due to a rectangular head is given by Lindholm [8] which also includes interaction effects when the length of the head is reduced to the order of the gap length (thin film head).

c) Gap Scatter Effect

Another example of a reproduce loss is that due to a gap which is not straight. Gap scatter refers to the gap length being constant across the head but the gap position varying in a statistical manner. If the distribution is Gaussian with scatter of spread σ, then the loss can be shown to be

$$\text{Scatter Loss (dB)} = -\frac{170}{\lambda^2}\left(\sigma_{rec}^2+\sigma_{play}^2\right) \qquad (2)$$

where non-correlated scatter for the reproduce and record head are included [9]. For example, if $\sigma_{rec}=\sigma_{play}=6\mu$" and $\lambda=60\mu$" the loss is 4 dB. For a common record-reproduce head this loss will not occur except due to fluctuations due to tape stretching.

Undesired Signal Effects There are two primary factors which lead to extra signal components that will deteriorate the picture quality. One is noise which arises from the granularity of the tape and the random fluctuations in bulk properties, such as pigment loading surface and smoothness. The other is signal interference which arises primarily from crosstalk between adjacent channels. Both these phenomena are discussed in this section.

1. Noise can be separated into *additive* and *modulation* components. Additive noise arises from the granularity or particulate nature of the media and is always present independent of the signal level. As the tape passes the reproduce head the flux from each particle threads the reproduce head (Fig. 18) yielding a voltage pulse. These pulses occur randomly since the particles are distributed randomly in the tape. The noise power spectrum has been calculated based on the phenomenon, excluding interparticle correlation [10]. In addition, signal-to-noise ratios for video recorders have been calculated based on the signal spectra given above and the particulate noise power spectrum. The derivation for the signal-to-noise ratio involves parabolic weighting of the noise power to include FM triangula-

tion effects [11]. The result is

$$SNR = \frac{3nWV^2m^2}{8\pi f_c f_s} \qquad (3)$$

where

n = *particle density*

W = *trackwidth*

V = *speed*

m = *modulation index*

f_c = *carrier frequency*

f_s = *video bandwidth*

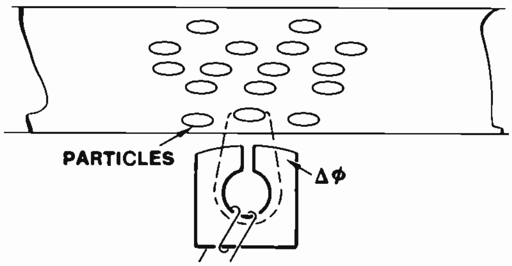


Fig. 18 Flux Contribution From Each Particle as a Source of Noise

The SNR varies as the trackwidth W, so that halving the trackwidth only reduces the SNR by 3 dB. n is the number of particles per unit volume: the use of smaller particles in the tape will increase the SNR. For fixed frequency operation, higher speeds will improve the SNR. However, for shorter wavelengths ($f_c/v, f_s/v$) the SNR will decrease. Almost all SNR expressions, independent of the particular application, vary linearly with trackwidth and inversely as the square of the shortest wavelength. Thus, in designing for higher densities it is always better to narrow the trackwidth rather than to shorten the wavelength. For example, the SNR of a transverse scan quadruplex video tape recorder, broadcast quadruplex recording (Ampex AVR1) with W = 10 mils, V = 1500 ips, f_c = 9 MHz, f_s = 4.5 MHz, $m \approx .75$ and n = 10^{14} particles/cc yields:

$$SNR \approx 56dB(P-P/RMS).$$

The above number is higher than measured, and one contributing factor may be additional noise due to modulation effects. Modulation noise is proportional to the signal level and arises from processing variations of media density and surface smoothness. The former affects the saturation magnetization and therefore the signal (M_r in Eq. 1) and the latter modulates the reproduce spacing loss (e^{-ka} in Eq. 1). All sources of modulation noise contribute to the *broadband*, or *luminance, noise*. *Chroma noise* is seen as a fluctuating disturbance in highly saturated areas of the picture and can be due primarily to fluctuations in head-to-tape spacing. As discussed in Section 5.2, the reproduce voltage of an FM video recorder is *straight line equalized*. Any variations which change the ratio of lower to upper side band voltages proportionately, corresponding to a change only in the slope of the straight line equalization, will not introduce noise. However, head to tape spacing fluctuations due to tape roughness cause non-linear changes (by changes in the exponential spacing loss e^{-ka}) and will introduce chroma noise in the form of a visible *flicker*.

2. Side Reading Phenomena

The most common signal interference effect is that due to side reading of adjacent channels and yields cross talk in the reproduce channel. As shown in Fig. 19, as the video head is reproducing one track the flux generated by a recorded adjacent track will circulate through the nearby high permeability reproduce head. The on-track signal will thereby have a small additional signal due to the adjacent tracks. The phase of these cross talk signals will be somewhat random since signals are not recorded coherently from track to track. Therefore the side recording terms will resemble a noise and cause errors in, for example, reading of the zero crossings in video FM recording. This phenomenon has been computed by Lindholm [12]. An approximate formula for this side-reading ratio (SSR) may be written as

$$SRR = e^{-kG}\,[1-e^{-kW}]/kW \qquad (4)$$

This is the ratio of adjacent tracks side reading voltage to the on-track signal. It involves the worst case when two adjacent tracks are adding in phase. G is the guard band and W is the trackwidth.

For a practical case of video recording the side reading equation(4) is evaluated directly for λ = 2 mils, W = 10 mils, and G = 2 mils. The result is

$$SRR = -85 \text{ dB}$$

For shorter wavelengths the side reading is even less due to the side spacing loss e^{-kG} Side reading is a long wavelength phenomenon and is strongly dependent on the guardband. Different estimates can be obtained comparing the isolated pulse peak voltage on track and off-track.

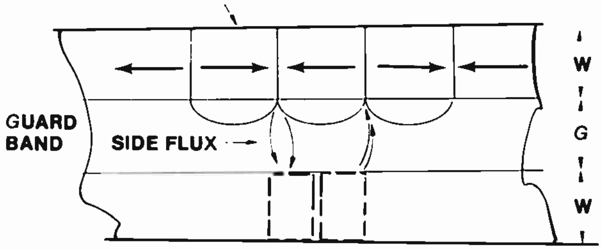


Fig. 19 Side Reading Flux Schematic

2.4 BASIC PROPERTIES OF MAGNETIC MATERIALS (Gooch) The performance of a magnetic tape recorder depends heavily on the properties of the magnetic materials used to make the recording heads and tapes. Today's magnetic materials are the product of sophisticated metallurgy and advanced manufacturing techniques, which in large measure are responsible for the advancement of the magnetic recording technology.

Magnetic materials fall into two basic categories: they are magnetically *hard* or magnetically *soft.* Both types of materials are used in magnetic tape recorders.

The hard magnetic materials are so called because of their ability to retain magnetism after being exposed to a magnetic field. The measure of this property is called *remanence*. These materials may be further characterized by their high *coercivity* and low *permeability. Coercivity* is the resistance of the material to being magnetized or demagnetized. *Permeability* is a measure of the magnetic conductivity relative to air.

In magnetic recording, hard magnetic materials are chiefly used in the manufacturing of recording tape and other related media. Some examples include gamma ferric oxide, iron oxide and chromium dioxide. Hard materials are also used to make permanent magnets for use in loud speakers, electric motors and other applications.

On the other hand, soft magnetic materials such as Alfesil, hot pressed ferrite, and Permalloy, exhibit low coercivity, low remanence, and relatively high permeability. These materials are used to make cores for magnetic heads.

Ferromagnetic materials have permeabilities much greater than unity, and show a strong magnetic effect. Ferromagnetism is exhibited mostly by metallic elements such as iron, cobalt, nickel and magnetic metals which are alloys of these elements. With the exception of ferrites,[15,16] most magnetic materials used in tape recorders are ferromagnetic.

Paramagnetic substances have permeabilities which lie between 1.000 and 1.001. These materials do not show hysteresis, and their permeabilities are independent of field strength. Some examples of paramagnetic materials are sodium, potassium, oxygen, platinum, and ferromagnetic metals above the Curie temperature.[15].

Diamagnetic materials have a permeability slightly less than 1. Many of the metals and most nonmetals are diamagnetic.[15]

Magnetic anisotropy is the term applied to magnetic materials that exhibit preferred directions of magnetization. These preferred and non-preferred directions are referred to as the *easy* and *hard* axes of magnetization, respectively. The higher the magnetic anisotropy, the harder it is to change the magnetization away from the preferred direction. In most polycrystalline materials, the crystals are randomly orientated and are magnetically isotropic. Single crystal ferrites and magnetic particles used in tape coating are examples of magnetic materials that are anisotropic.[13,15]

Table 2 shows properties of materials commonly used in magnetic heads and tapes. CGS units are used throughout this section. Conversion factors to change to MKS units are given in Table 3.

Table 2 Properties of Soft Magnetic Materials

Material	$B_s = 4\pi M_s$ Gauss	H_c Oersted	B_r Gauss	μ (DC) Initial	Resis-tivity	Thermal Expn.	Curie Temp.	Vickers Hardness
Iron Fe	21,362	1	-	20,000	-	-	-	-
HI-MU80 80 Ni, 4.6 Mo, Mn.5, 15 Fe	8300	.02	-	50,000	65 μohm-cm	13 x 10^{-6} cm/cm/°C	773°C	127
Alfesil (Sendust) 85 Fe, 6 AL, 9SI	10,000	.06	-	10,000	90 μ ohm-cm	≈11 x 10^{-6} cm/cm°C	773°C	496
MnZn Hot Pressed Ferrite	4500	.02-.2	≈900	2000-5000	10-100 ohm-cm	10-15 x 10^{-6} cm/cm°C	100-300 °C	650-750
NiZn Hot Pressed Ferrite	3000	.15-.3	≈1800	100-2000	10^3-10^6 ohm-cm	7-9 x 10^6 cm/cm°C	150-200 °C	700-750

Properties of Hard Magnetic Tape Materials

Material	M_s Gauss	$B_s = 4\pi M_s$ Gauss	H_c Oersted	B_r Gauss	Square-ness Ratio
Gamma Ferric Oxide	400	5026	300- 350	1300*	.75*
Chromium Dioxide	470	6000	300- 700	1600*	.9*
Metal Particles	800	10,000	1000	3500*	.8*

*Values are typical for finished tape.

Table 3 Conversion Factors from CGS to MKSA or SI Units

Parameter	CGS Units	Multiply By	To Obtain MKSA Units
Flux Φ	Maxwell	10^{-8}	Webers (Wb)
Flux Density B	Gauss	10^{-4}	Webers/meter^2 = 1 Tesla(T)
Magnetization M	Gauss 1 gauss = 1 EMU/CM^3	10^3	Ampere turns/meter (At/m)
Permeability μ_o of free space	1	$4\pi \times 10^{-7}$	Henry/meter (H/m)
Magnetomotive Force F	Gilberts	$\frac{1}{.4\pi}$	Ampere turns (At)
Field H Magnetomotive Force per Unit Length	Oersted	$\frac{10^3}{4\pi}$	Ampere turns/meter (At/m)

Basic Theory of Magnetism Magnetism results from two sources: orbital motion of electrons around the nucleus, and the electrons spinning on their own axes (See Fig. 20). Both the orbital and spin motion contribute to the *magnetic moment* of the atom, although in most magnetic substances almost all of the magnetic moment is due to the spin motion. As the electron spins on its axis, the charge on its surface moves in a circular pattern. This moving charge in turn produces a current that creates a magnetic field. This phenomenon occurs in all substances. However, the electrons of the atoms in non-magnetic materials occur in pairs with the spins in opposite directions, balancing each other and rendering the atoms magnetically neutral. The atoms can only produce the external effect of a magnet when the electron spins are unbalanced.

The iron atom, for example has 26 electrons in rotation around its nucleus (see Fig. 21). These orbiting electrons occur in regions called *shells*. According to quantum theory, the maximum number of electrons that can exist in each shell is $2N^2$, where N is the number of the shell. Starting from the nucleus, the first, second, third and fourth shells could have a maximum number of 2, 8, 18 and 32 respectively. The maximum number of electrons in each shell may not be reached before the next shell begins to form. The iron atom actually has two electrons in the first shell, the second has eight, the third and fourth shells have fourteen and two respectively. The plus and minus signs show the direction of the electron spins. The electron spins in the first, second, and fourth shells balance each other and produce no magnetic effect. It is the third shell that is of particular interest in the iron atom. In this shell there are five electrons with positive spins and one with a negative spin, which gives the atom a net magnetic effect.

The thermal agitation energy, even at low temperatures, would prevent the atomic magnets from being aligned sufficiently to produce a magnetic effect. However, powerful forces hold the electron spins in tight parallel alignment against the disordering effect of thermal energy. These forces are called *exchange forces*.

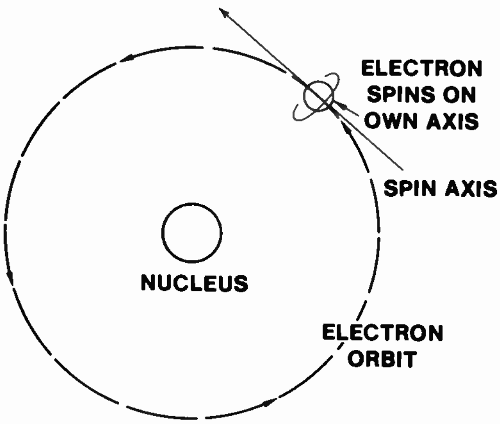


Fig. 20 Electron Motions

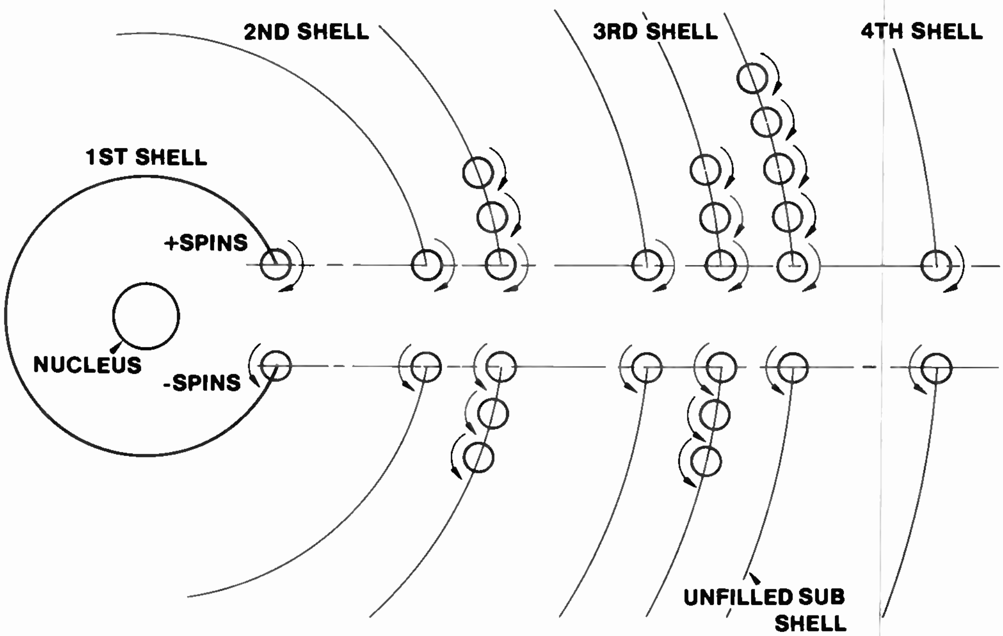


Fig. 21 Schematic Diagram of Iron Atom

The parallel alignment of the electron spins, due to the exchange forces, occurs over large regions containing a great number of atoms. These regions are called *domains*. Each domain is magnetized to saturation by the aligned electron spins. As this magnetization occurs with no external field applied, it is referred to as *spontaneous magnetization*. When the magnetic material is in the demagnetized state, the direction of the magnetization of the saturated domains is distributed in a random order, bringing the net magnetization of the material to zero. The domains are separated from each other by partitions called *Bloch walls*.[13,15] The domain wall pattern is determined by the strains within the material, and its composition.

In soft magnetic materials the magnetization takes place by the displacement of the domain walls.[13,15,16]. The wall movement is not continuous but occurs in discrete steps called *Barkhausen steps* or *jumps* that are related to imperfections or inclusions in the crystalline structure of the material.

The particles used in magnetic tape coating are so small that Bloch walls do not form. They behave as single domain particles which are spontaneously magnetized to saturation. Irreversible magnetization is achieved only through irreversible rotation of the individual particle magnetizations.[17,19].

Curie Point The Curie point is the temperature at which the thermal agitation energy overcomes the exchange forces. The spontaneous magnetization disappears and the material is rendered non-magnetic. This process is reversible; when the temperature is lowered below the Curie point the spontaneous magnetization returns and the material is again magnetic. Figure 22 shows the effect of temperature on the permeability of a typical ferrite.

Magnetic Induction When a current I is connected to a solenoid coil of N turns, a magnetic field H_A is created which has direction as well as strength, and is defined by

$$H_A = \frac{.4\pi\ NI}{l} \qquad (1)$$

where H_A is in oersteds
l is the length of the solenoid in cm.
I is in amps

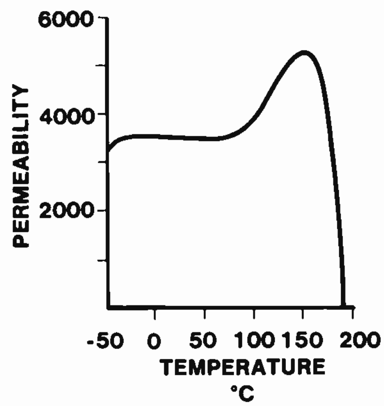


Fig. 22 Permeability vs Temperature

As a result of the field H_A, flux lines are produced in the surrounding space. The flux lines form closed loops which flow from one end of the solenoid coil, into the air, and re-enter the coil at the opposite end. The measure of the intensity, or the concentration of the flux lines per unit area, is called the *flux density*, or the *induction*, *B*.

Figure 23 shows that with no magnetic material present in the solenoid coil the flux density B is relatively low and is equal to the applied field H_A. When a piece of magnetic material is placed in the solenoid coil, the flux density is increased (see Fig. 24). This results from the magnetic moments[14,15] of the electron spins aligning themselves with the applied field H_A, causing the magnetic material to become a magnet. The sum of the magnetic moments per unit volume is the magnetization M. The magnetization of a material creates magnetic fields. Inside the material these fields are called *demagnetization fields* because they oppose the magnetization. Outside the material, they are called *stray* or *fringing fields*. The net field acting on the material is the vectorial sum of the demagnetization field and the applied field. The flux density is the net field plus the magnetization M, i.e.,

$$B = H + 4\pi M \qquad (2)$$

where H is the net field
M is in gauss
B is in gauss

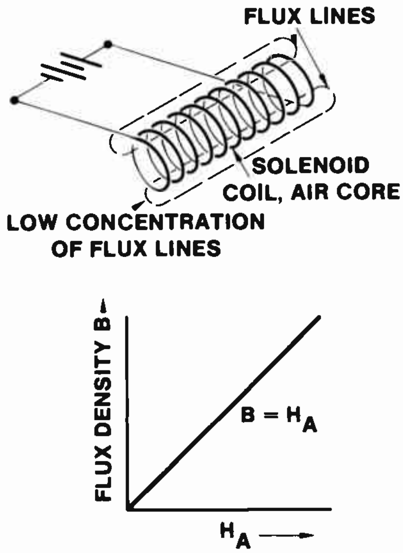


Fig. 23 Flux From Air Core Solenoid

Initial Magnetization B-H Curve The relationship of the induced flux density B and the net field H of soft magnetic materials are typically described by the initial B-H magnetization curve and the B-H hysteresis loop.

Figure 25A shows the initial magnetization curve of a typical soft magnetic material. This curve is obtained by starting with a toroid ring in the demagnetized state and plotting the flux density B against the field H. The demagnetization field in a toroid ring is zero; the net field is therefore equal to the applied field. The slope of the initial magnetization curve is the permeability μ, defined by

$$\mu = \frac{B}{H} \tag{3}$$

In CGS units the permeability is a dimensionless ratio, and represents the increase in flux density relative to air caused by the presence of the magnetic material. The permeability can also be defined in terms of the magnetization M as

$$\mu = 1 + \frac{4\pi M}{H} \tag{4}$$

Starting at the origin, the curve has a finite slope which is the initial permeability. As the field H is increased, the slope becomes steeper. This is the *maximum permeability* region. The value of the maximum permeability is determined with a straight line of the steepest slope that passes through the origin and also contacts the magnetization curve. Finally, as H is further increased, a point is reached on the initial B-H curve where the magnetization approaches a finite limit indicated by the dotted line. At this point the magnetization of the material does not increase with further increases in the field. This is the saturation flux density B_s which is equal to the spontaneous magnetization of the magnetic material. After the material has reached saturation, the slope of the B-H curve changes and the flux density B continues to rise indefinitely at the rate of B equal to H_A as if the magnetic material were not present. Figure 25B shows a plot of the permeability as a function of the field.

Hysteresis Loop: If the H field is decreased after the initial magnetization curve reaches the saturated state, it is found that the induction does not follow the same initial curve back to the origin, but traces a curve called the hysteresis loop which is shown by Fig. 26. As the magnetization is gradually decreased from the saturation point C it follows along the lines CD and reaches a finite value B_r, the *remanence,* which is the flux density remaining after removal of the applied field. In order to reduce the remanence to zero, a negative field, the coercive force H_c, must be applied. The curve from D to E is the demagnetization curve. As H is further increased in the negative direction, the magnetization will proceed from E to F and the material will eventually become saturated in the opposite direction. If at this point the field is again reversed to the positive direction, the magnetization will trace the line F, G, C and the hysteresis loop is completed.

Hysteresis Losses: The area of the hysteresis loop is the energy necessary to magnetize a magnetic substance. This energy is expended as heat. The loop area is a measure of the heat energy expended per cycle per unit volume, and is called the

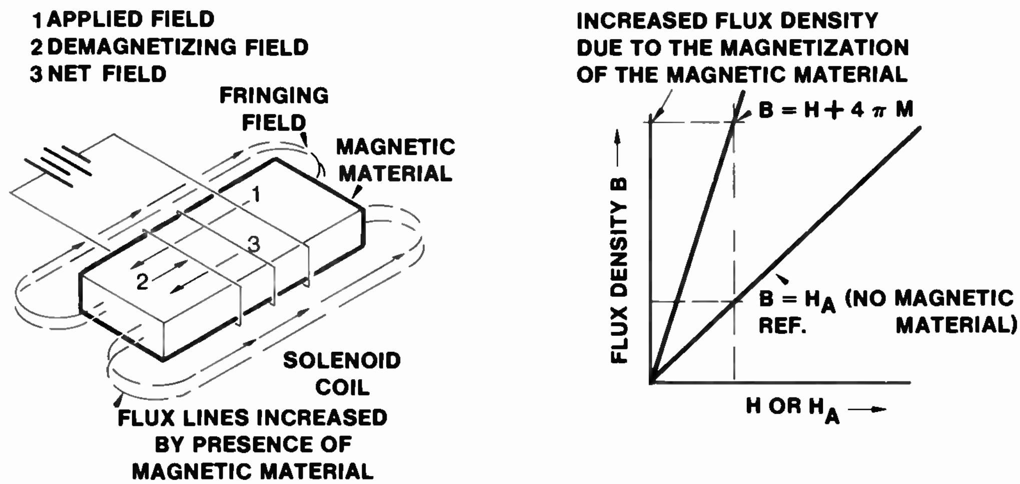


Fig. 24 Increase in Flux with Magnetic Core Material

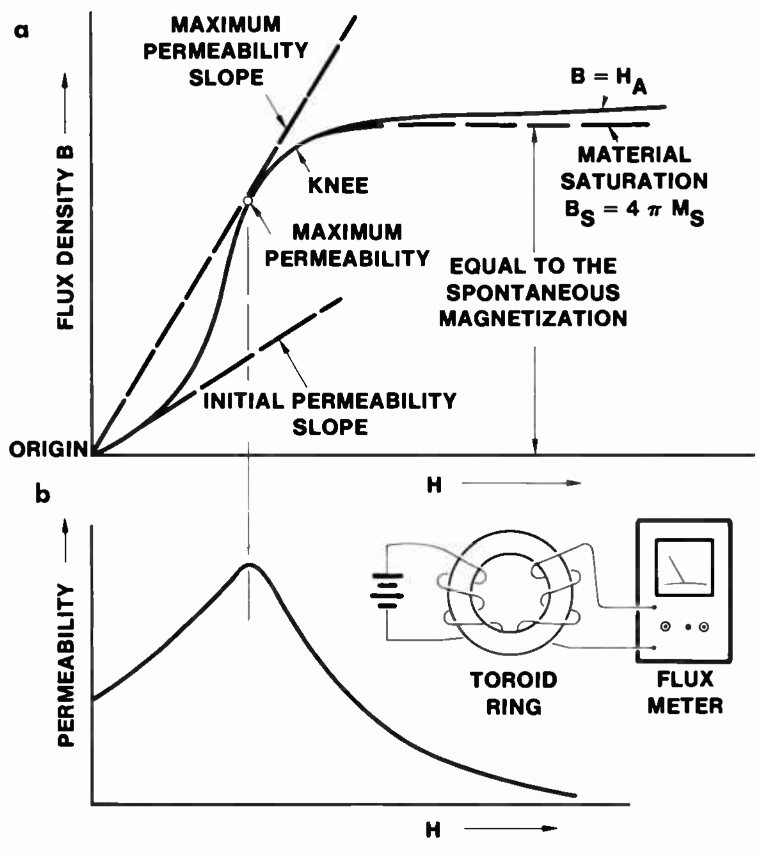


Fig. 25a Initial B-H Curve

Fig. 25b Permeability vs H Field

hysteresis loss.

$$W_h = \frac{A}{4\pi} \; ergs/cm^3/cycle \qquad (5)$$

A practical expression for power loss P in watts is given by,

$$P = \frac{fal}{4\pi} \times A \times 10^{-7} \qquad (6)$$

where A is the area of the loop in gauss-oersteds
f is the frequency in Hz
a is the cross sectional area of the core in cm^2
l is the magnetic path length in cm

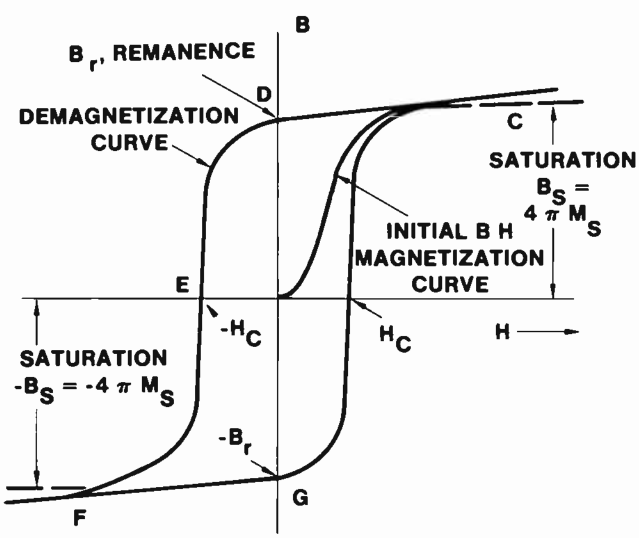


Fig. 26 B-H Loop

Figure 27 shows a comparison between the hysteresis loops for hard and soft magnetic materials. As indicated by the difference in the areas of the loops, more energy is required to magnetize the hard magnetic materials.

Permeability Measurements: A simple method for measuring the low frequency permeability (below 10,000 Hz) of soft magnetic materials used in magnetic head cores is illustrated by Fig. 28. The effect of core losses and the measurement of high frequency permeability is discussed in Section 2.5 on head design.

Figure 28 shows a toroid ring with a thickness T and a mean length l wound with a primary and secondary coil. The ring is typically composed of a number of laminations of the same thickness that is to be used in the head. Because ferrite head cores are not laminated structures, the toroid ring is typically made from a solid piece of the material to be evaluated.

An alternating current I is applied to the primary coil while the secondary coil is connected to an ac volt meter. The ac field thus created produces a time changing flux in the secondary coil, which in turn produces a voltage that is proportional to the rate of change of the flux. By means of an integrating circuit, a hysteresis loop can also be produced on an oscilloscope screen.

If the ac field is varied in amplitude from a low to a high value, or vice versa, a family of minor hysteresis loops is traced, as shown by Fig. 29. The peak value of the flux density and the ac field corresponds to a line through the tips of these minor loops which closely approximates the initial magnetization curve. The slope of this curve is the ac permeability. The initial and maximum permeabilities are defined in the same manner as previously indicated.

The ac permeability may be determined by the following procedure.

1. Select the flux density that corresponds to the initial permeability on the magnetization curve, which for most magnetic head materials is approximately 40 gauss.
2. Calculate the peak ac output voltage E.

$$E = 2\pi \, BAN \, f \, 10^{-8} \qquad (7)$$

where B is the flux density in gauss
N is the number of turns
f is the frequency in Hz
A is the cross sectional area of the toroid ring in cm^2

3. Adjust the current applied to the primary coil to give the voltage calculated in Step 2.
4. Measure the current applied in Step 3, and determined the H field.

$$H = \frac{.4\pi NI}{l} \qquad (8)$$

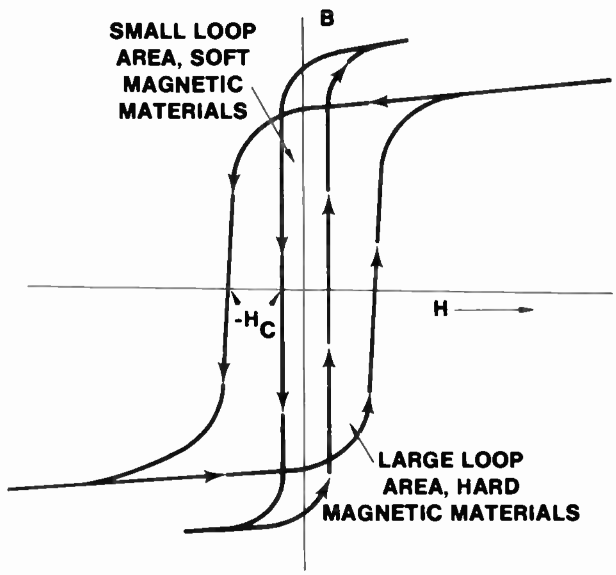


Fig. 27 B-H Loops for Hard and Soft Materials

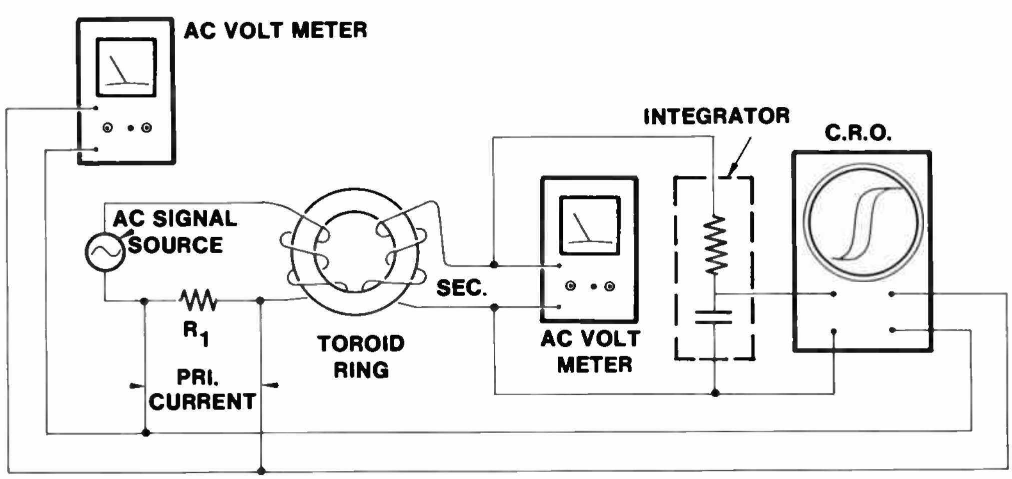


Fig. 28 Measurement of Permeability and B-H Loop for Soft Materials

where N is the turns
I is the peak current in amps
l is the mean length of
the toroid ring in centimeters

5. Now calculate μ as

$$\mu = \frac{B}{H} = \frac{40\ gauss}{H}$$

As the flux levels in magnetic heads are relatively low, the initial permeability is of prime interest. However, ac permeability at any flux density may be determined by the foregoing procedure.

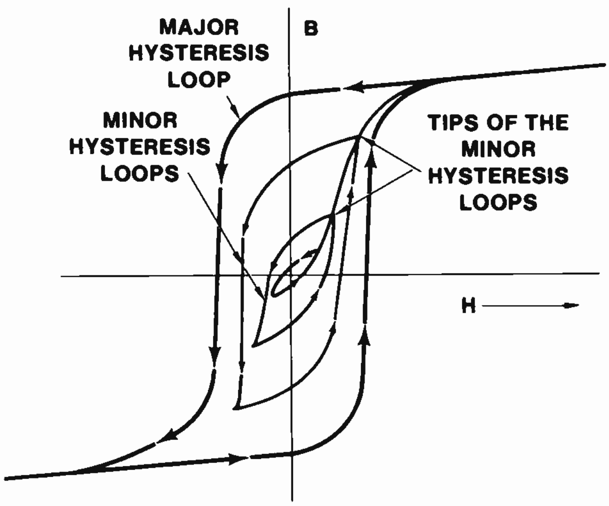


Fig. 29 Minor Hysteresis Loops

Initial M-H Curve and M-H Hysteresis Loop: The initial M-H curve and M-H hysteresis loops are plots of the magnetization M versus the net field H, and are typically used to describe the intrinsic properties of hard magnetic materials such as those used in recording media. An initial M-H curve is shown in Fig. 30 The slope of the M-H curve is the *susceptibility* x, and is defined by

$$x = \frac{M}{H} \quad (9)$$

The permeability may be related to the susceptibility by

$$\mu = 1+4\pi\chi \quad (10)$$

When the saturation magnetization M_s is reached, the M-H curve approaches a finite limit and does not increase indefinitely as in the case of the B-H curve.

If at the saturation point of the initial M-H curve, the applied field is made to follow the same sequence as previously outlined for the B-H loop, an M-H hysteresis loop will be traced (see Fig. 31).

The ratio of the remanent magnetization M_r to the saturation magnetization M_s is called the *squareness ratio*, and is an important parameter in evaluating the magnetic orientation of the particles in magnetic tape. The squareness ratio is 1.0 for perfectly oriented particles. More practical values for oriented particles range from 0.7 to 0.9. Randomly oriented particles are approximately 0.5.

The vibrating sample magnetometer is used for measuring magnetic properties of recording media materials. A schematic representation of such a device is shown in Fig. 32. The tape sample is vibrated in the magnetic field of the electromagnets, and the magnetic moment is measured in terms of the induced voltage in a pair of coils in which the exciting field from the electromagnets has been balanced out. In addition to the magnetic moment, the vibrating sample magnetometer can be used to measure such properties as coercivity and remanence.[17,20,21]

Hysteresis loops for magnetic media are usually obtained by an air core B-H meter as shown in Fig. 33, in which the field supplied by a solenoid coil is driven from a 60 Hz source. The tape sample is placed inside a small search coil connected in series with an identical coil to balance out the applied field. The signal from the search coil is amplified and integrated to obtain a voltage that is proportional to the flux from the tape sample.[17,20]

Demagnetization If a short bar of magnetic material is magnetized by an applied field H, poles are created at each end. These poles in turn create a magnetic field in the opposite direction to the applied field. This opposition field is called the demagnetizations field H_d (see Fig. 34). The net field H acting on the bar is

$$H = H_A - Hd \quad (11)$$

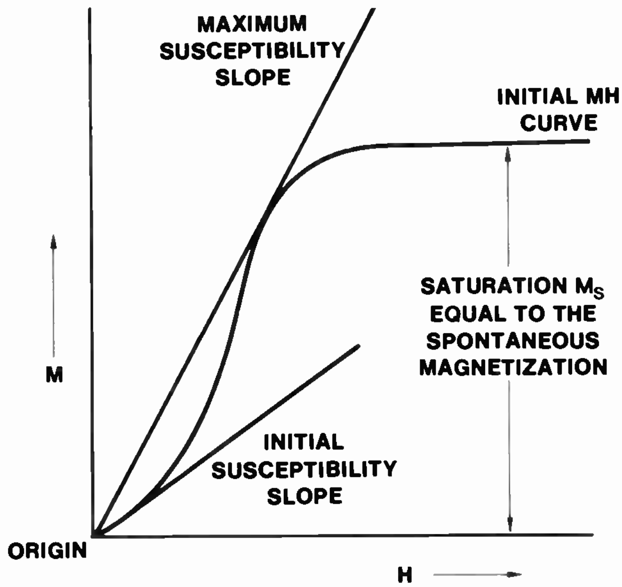


Fig. 30 Initial M-H Curve

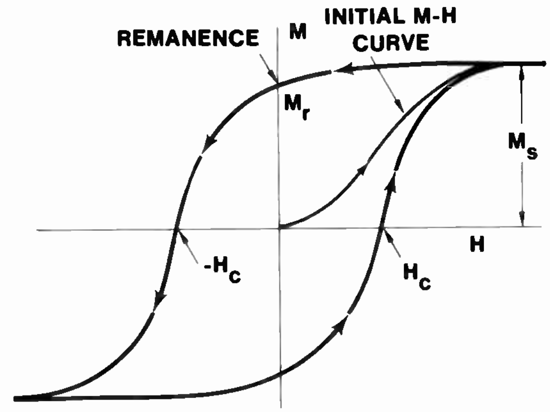


Fig. 31 M-H Hysteresis Loop

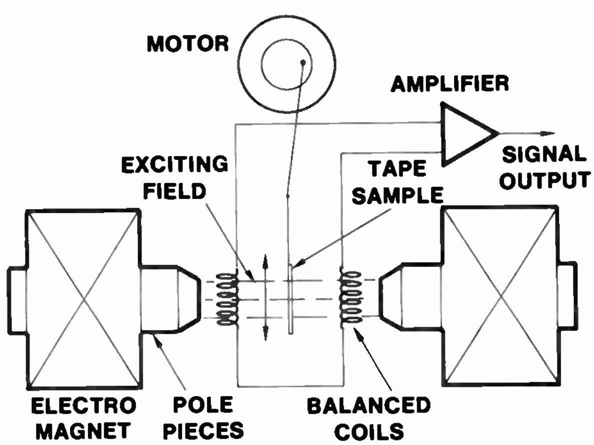


Fig. 32 Vibrating Sample Magnetometer

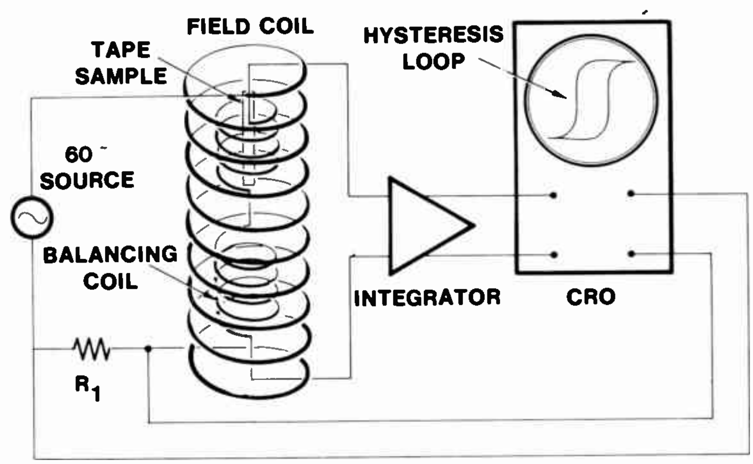


Fig. 33 Loop Tracer

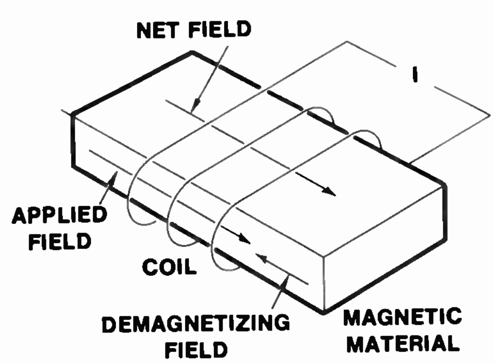


Fig. 34 Demagnetization Field

The demagnetizing field H_d is dependent on the shape of the magnetic object and the magnetization M[13,15].

The demagnetization field is zero in a ring core with no air gap. However, when an air gap is cut creating poles at the gap confronting surfaces, the resulting demagnetization field shears the hysteresis loop from the original position. This effect is shown by Fig 35.

To bring a magnetic substance to a demagnetized state a field that is equal to the coercive force H_c must be applied. However, upon removing this field the residual flux density will rise to a value B_1 as illustrated by Fig. 36. It is possible to reduce this residual flux density to zero by increasing the demagnetization field to a value greater than H_c and then decreasing it to zero as shown by the dashed lines. This technique requires a knowledge of the magnetic history of the material.

A more effective method to completely demagnetize a magnetic material is demagnetization by reversals. In this method the material is first saturated by an ac field, then cycled through a series of diminishing field reversals as shown by Fig. 37. The magnetic material will be left in a demagnetized state when zero field is reached regardless of its magnetic history. This technique is used to bulk erase magnetic tape and other recording media, by exposing it to a strong ac field and then slowly removing the magnetic media from the field.

2.5 HEAD DESIGN (Gooch) The ring head was invented in 1935 by E. Schiller of Germany. In the intervening years, magnetic heads have become a highly developed technology and are used in a wide variety of applications for entertainment and data storage.

The heads on a magnetic tape recorder are the means by which the electrical signals are recorded on and reproduced from a magnetic tape. The record head is a transducer that changes the electrical energy from the signal system into a magnetic field that is emitted from a physical gap in the head. The field impresses a magnetic pattern on the tape proportional to the electrical signal. The reproduce head, on the other hand, is a transducer that collects the flux from the tape across a physical gap and changes it into an electrical signal that is proportional to the recorded flux.

Ring-type magnetic heads are composed of two highly permeable magnetic cores, with a nonmagnetic gap spacer and a coil to which the signal information is connected. Today most of the magnetic cores for video heads are made from either polycrystalline hot-pressed ferrite or single-crystal ferrite. However, for some video applications Alfesil (Sendust) is used, which is a hard-cast alloy composed of aluminum, iron, and silicon. Audio head cores typically use Permalloy-type materials.

The basic objective in magnetic head design is to achieve the highest possible head efficiency, which for a playback head is the ratio of the core flux to the total available tape flux. The record head efficiency is the proportion of flux generated by the coil that reaches the gap and results in a useful field to magnetize the tape. Additionally, an important design requirement regarding the record head is that the gap fields do not exceed the saturation induction of the gap pole tips.

The critical design considerations that dictate the performance of magnetic heads are track width, gap length, gap depth, core geometry (e.g., path length), and the magnetic properties of the head core materials. Each of these parameters must be selected in accordance with the design criteria of the magnetic tape recorders, and at the same time, maintain the head efficiency as high as possible. Often such requirements as short wavelength resolution, head life and high record fields required to drive high coercivity media conflict, and some design tradeoffs are necessary.

The performance of magnetic heads depends heavily on maintaining accurate mechanical dimensions. To meet the short wavelength demands of today's video recorder, the gap edges must be well defined and straight, which requires that the gap confronting surfaces be lapped to a high degree of flatness. The gaps in ferrite video heads are created by using sputtering techniques to deposit a thin film of glass or silicon dioxide (S_iO_2) on the gap confronting surfaces, and then glass bonded to prevent edge erosion. The sides of small video tracks (less than 0.003 in, or 0.076 mm) are typically supported with glass or other means to provide protection against the stresses involved when running in contact with tape at high velocities.

While the discussions in this section are directed primarily to video heads, the basic principles and design considerations presented apply to all ring-type heads.

Thin film integrated heads are in increasing demand for computer disc applications; however, for video and audio recorders they are of limited interest and will not be addressed. The reader is referred to the many papers on the subject.

Magnetic heads have many facets, and only the basic principles can be covered. The information presented here is intended only to give a basic understanding of the essential characteristics of ring-type magnetic heads.

Basic Structure The basic elements of a typical video head core are shown in Fig. 38. The core material is either a magnetic metal such as Alfesil, (Sendust) or a ferrite. Ferrites are used in most present-day video heads because of their superior magnetic properties and long life. To create a non-magnetic gap of controlled dimensions, the core is constructed in two half-sections. To facilitate this construction, the gap spacer usually runs the entire length of the core. The gap confronting surfaces are lapped to a high finish to ensure a sharp, well-defined edge. A winding aperture is cut either in one half, or in each half, to allow the signal coil to be wound on the core. The coil aperture is located directly beneath the front gap area. The front gap area is determined by the gap depth and the track width.

The rear gap area comprises the remainder of the core and is made much larger than the front gap. The tape contact surface is shaped to conform to the requirements of the scanner to provide intimate contact with the tape.

Basic Record Head Magnetic Circuits The effect of the head core parameters and how they may be optimized to achieve maximum head efficiency can be more easily understood by considering simple electrical circuits that are analogous to the magnetic circuits. Figure 39a is a plan view of the video core shown in Figure 38, when connected as a record head. Figure 39b shows an electrical analog of the magnetic circuit, in which the gap and core reluctances and the magnetomotive force (mmf) are represented by resistances and voltage (emf), respectively.

When a current I is applied to the coil of N turns, a magnetomotive force (mmf) is produced, with a magnitude proportional to the current and the number of turns (mmf in CGS units is $.4\pi NI$). As a result of this magnetomotive force, a flux Φ flows in the magnetic core. This flux is analogous to a current in the electrical analog and thus the relationship that exists among magnetomotive force, flux, and reluctance of magnetic circuits is analogous to voltage, current, and resistance in electrical circuits. The basic equation for magnetic circuits can be written as

$$F = 0.4\pi NI = \phi R \qquad (12)$$

where

ϕ is the flux
R is the reluctance
F is the magnetomotive force

Reluctance (R) is the magnetic resistance and is related to the core geometry and permeability in the same manner as resistance is related to the physical dimensions and conductivity of a wire. Thus, to make the analogy, the wire resistance is given by

$$R = \frac{1}{\gamma} \cdot \frac{l}{A} \qquad (13)$$

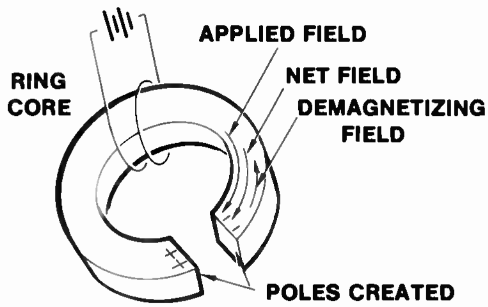
where

l is the length of the wire
A is the wire cross sectional area
γ is the conductance.

Therefore, the corresponding magnetic resistance or reluctance is defined by

$$R = \frac{1}{\mu} \frac{l_c}{A_c} \qquad (14)$$

where



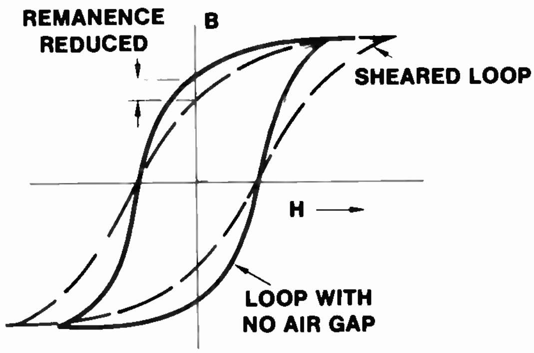


Fig. 35 Sheared Hysteresis Loop

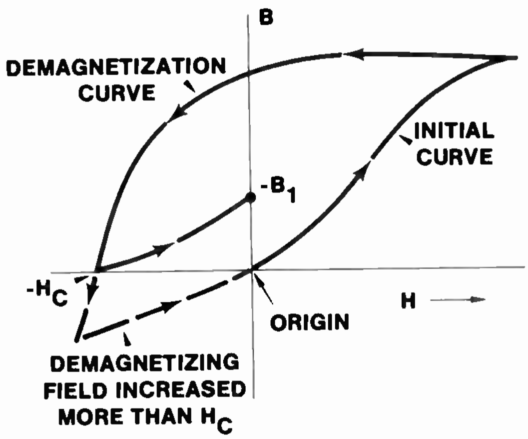


Fig. 36 Demagnetization Curve

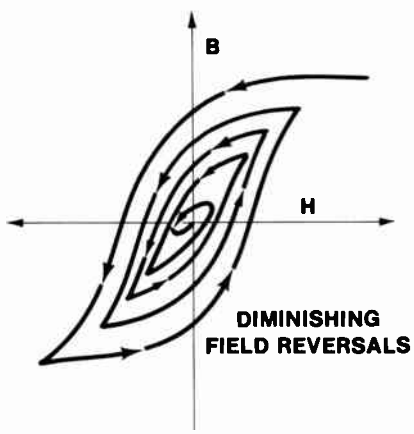


Fig. 37 Demagnetization by Reversals

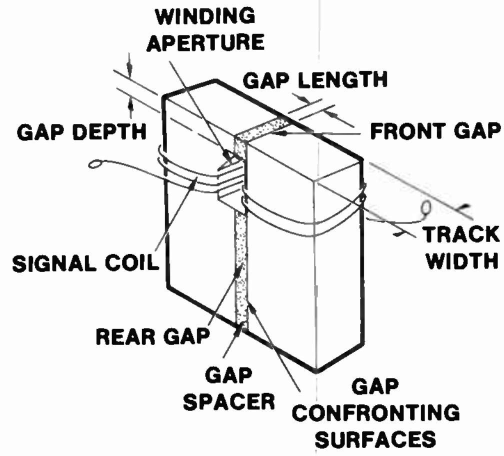


Figure 38 Typical Video Head Core

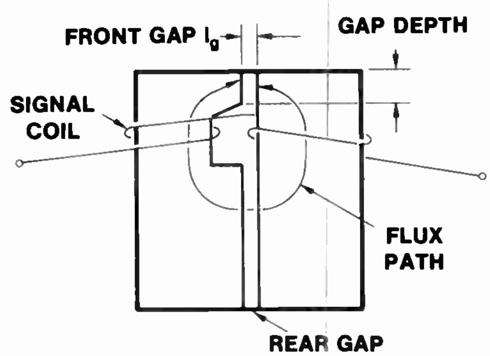


Fig. 39a Plan View of Record Head

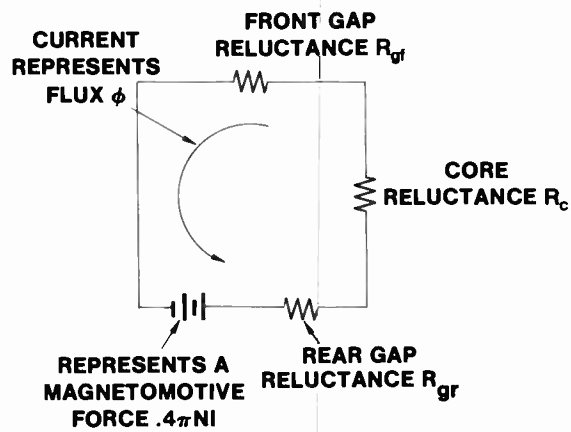


Fig. 39b Electrical Analog

l_c is the mean path length of the magnetic core, cm
A_c is the cross sectional area of the magnetic core, cm^2
μ is the permeability of the core material.

The reluctance for magnetic head cores may be defined more specifically in terms of core and gap dimensions, as

$$R_c = \frac{l_c}{\mu_c A_c} \qquad (15)$$

where

R_c is the reluctance of the core
l_c is the mean magnetic path length
A_c is the core cross sectional area
μ is the core permeability (As the result of core losses, the core reluctance is frequency dependent. Core losses will be discussed in more detail later).

and

$$R_g = \frac{l_g}{\mu_o A_g} \qquad (16)$$

where

R_g is the reluctance of the head gap
l_g is the gap length
A_g is the cross sectional area of the gap confronting surfaces
μ_o is the permeability of air, equal to 1 in CGS units.

The cross sectional areas of a magnetic head core are usually not constant. It therefore becomes necessary to calculate the reluctance of small segments of the core and sum the reluctance values of each segment. Thus, the total core reluctance becomes

$$R_{ct} = R_{c1} + R_{c2} + R_{c3} + \ldots\ldots + R_{cn} \qquad (17)$$

where

R_{ct} is the total core reluctance
R_{c1} ..... R_{cn} is the reluctance for each segment

Referring again to the electrical analog (Fig. 39b), each reluctance (resistance) has a potential drop that is equal to the value of reluctance times the flux. By Kirchhoff's Law, the potential drop across each series reluctance must equal the total magnetomotive force (voltage). The total mmf F_t is expressed thus

$$F_t = \Phi R_{gf} + \Phi R_{gr} + \Phi R_c \qquad (18)$$

The total mmf may also be written as:

$$.4\pi NI = \Phi R_{gf} + \Phi R_{gr} + \Phi R_c$$

By rearranging the equation the flux ϕ may be defined as:

$$\Phi = \frac{.4\pi NI}{R_{gf} + R_{gr} + R_c} \qquad (19)$$

The condition for high head efficiency exists when most of the flux generated by the coil appears across the gap, or a large voltage drop across R_{gf} and a small drop across R_c and R_{gr}. The head efficiency ϵ is, therefore, the ratio of the gap reluctance to the total core reluctance, which can be stated as follows:

$$\epsilon = \frac{\Phi R_{gf}}{F_t} = \frac{\Phi R_{gf}}{\Phi R_t}$$

$$= \frac{R_{gf}}{R_{gf} + R_{gr} + R_c} \times 100\% \qquad (21)$$

Basic Reproduce Head Magnetic Circuit
Figure 40 shows the electrical analog of a playback core, which is similar to the record head shown in Figs. 39a and b. Now, however, the flux source (Φ) is the available flux from a magnetized tape, instead of a current flowing in the record coil. When the flux source (Φ) is connected across the gap front reluctance R_{gf}, it enters the core and splits into two paths. One path is across the front gap reluctance R_{gf} and the other is through each half of head core reluctances $\frac{R_c}{2}$ and the rear gap reluctance R_{gr}. The tape flux Φ that flows through the head core links the coil and thereby produces an output voltage. However, the tape flux that is shunted by the front gap reluctance R_{gf} does not link the coil, and no contribution to the output voltage is made. The available flux from the tape that actually links the coil is determined by the ratio of the gap reluctance R_{gf} to the total reluctance R_t. Therefore, the reproduce flux efficiency ϵ can be written as

$$\epsilon = \frac{R_{gf}}{R_t} = \frac{R_{gf}}{R_{gf}+R_{gr}+R_c} \times 100\% \quad (21)$$

Shunt Reluctance The stray fluxes that fringes from the nonmagnetic front gap tends to enlarge the physical gap area. These effects can be visualized by referring to Fig. 41a and the electrical analog shown by Fig. 41b. The reluctance value R_{gf} as given by the physical dimensions (Eqn. 16) is shunted by additional reluctances, resulting from the stray flux, which are represented by R_{s1} and R_{s2}. R_{s1} is the combined shunt reluctance of the top and sides of the front gap region. R_{s2} is the shunt reluctance of the area beneath the front gap. The net effect of these shunt reluctances is to reduce the physical gap reluctance, which results in less potential drop across the front gap relative to the core, thereby reducing the head efficiency.

The shunt reluctances R_{s1} and R_{s2} may be estimated by the following approximations, which are derived from the work of E. Unger and K. Fritzsch [Ref. 9].

$$R_{s1} = \frac{\pi}{\left[2(gD) + T.W.\right] l_N \left(\pi \frac{l_s}{l_g}\right)} \quad (22)$$

$$R_{s2} = \frac{\phi}{T.W.\ l_N \left(\phi \frac{L}{l_g}\right)} \quad (23)$$

where

- $g.D.$ is the gap depth
- $T.W.$ is the track width
- l_s is one half of core length (see Fig. 42)
- l_g is the gap length
- L is the length shown in Fig. 42.
- ϕ is the total aperture angle in radians.

All linear dimensions are in centimeters.

The total shunt reluctance R_{st} is obtained by:

$$R_{st} = \frac{R_{s1} R_{s2}}{R_{s1} + R_{s2}} \quad (24)$$

The effective front gap reluctance R_{ge} can be determined by the following

$$R_{ge} = \frac{R_g R_{st}}{R_g + R_{st}} \quad (25)$$

To minimize the shunting reluctance (R_{S2}) beneath the front gap, the aperture angle, (Fig. 42), should be as large as possible. The optimum angle would be 90° relative to the gap line. However, if the aperture angle is made excessively large, a high stress point is produced and the pole tip area is subject to damage. This is especially true with ferrite video heads that operate at gap depths below 0.002 in. Typical angles range from 60° to 45 ° relative to the gap line. The shunt reluctance of the rear gap region has a minimal effect on the rear gap reluctance, and may be neglected for most video head cores.

High Frequency Core Losses The effect of core losses on video heads is of particular significance, for as the operating frequency of the head increases, the permeability of the core materials decreases relative to the low frequency value, because of the effects of eddy currents and other residual core losses.

In low resistivity materials such as the magnetic metal alloys the reduction in permeability is primarily due to eddy currents. These losses force the flux to flow around the periphery of the core in the same manner as the high frequency skin effects in electrical conductors. Thus, the effective flux conducting area is reduced and the core reluctance is increased. The effect on the core permeability at high frequencies is illustrated with the aid of Fig. 43 and the skin depth equation for electrical conductors, which is

$$\delta = \frac{1}{2\pi} \sqrt{\frac{p}{\mu_{dc} f}} \quad (26)$$

where

δ is the skin depth
p is the resistivity
f is the frequency
μ_{dc} is the dc permeability

Referring to Fig. 43, the dc permeability is constant up to a frequency where the skin depth is equal to magnetic core thickness T. After f_1, the permeability of the core is reduced by the skin effects at the rate of 3dB per octave. The high frequency core reluctance may be found by calculating the effective cross sectional area at the

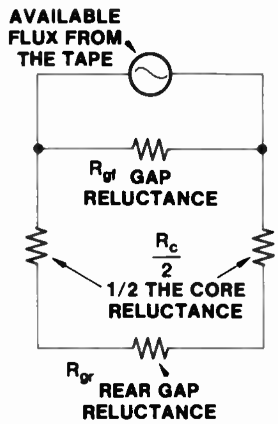


Figure 40 Electrical Analog of Playback Head

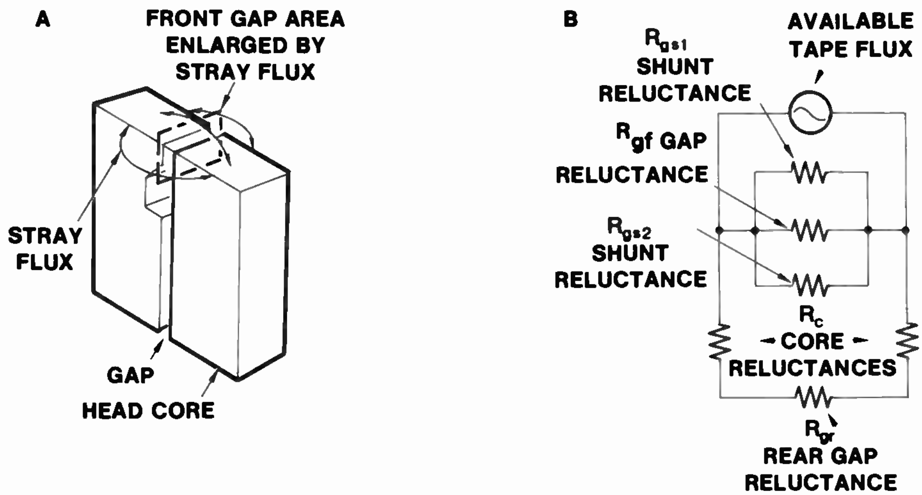


Figure 41a Effect of Shunt Reluctance

b) Electrical Analog

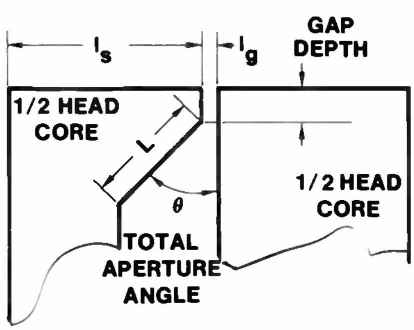


Figure 42 Aperture Angle

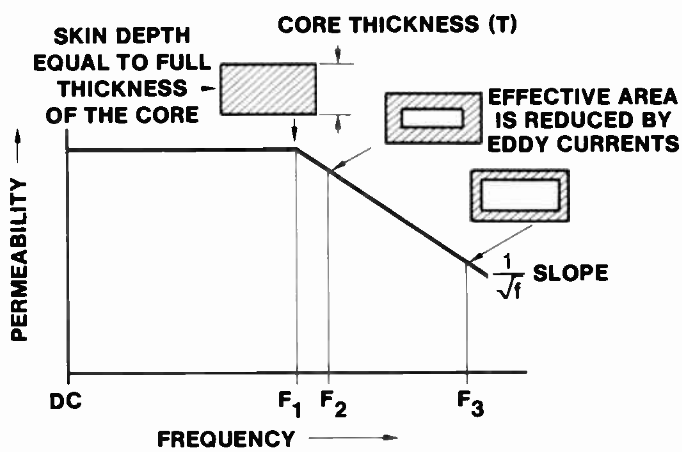


Figure 43 Effect of Eddy Currents on Permeability

frequency of interest and substituting the result for the low frequency cross sectional area Ac in Equation 4. However, this method is not very applicable to ferrite materials where the high frequency losses are primarily due to the spin relaxation effects[42], and the eddy currents are significantly reduced due to the relatively high resistivity of these materials. A more convenient way to quantify all losses for both metal and ferrite magnetic material is to treat the core permeability as a complex function which may be expressed as

$$\mu_f = \mu' - j\mu'' \tag{27}$$

where

μ_f is the value of the permeability as the result of core losses,
μ' is the real (magnetization) component
μ'' is the imaginary (loss) component

The core reluctance may now be defined in terms of the complex permeability. The basic reluctance relation

$$R_c = \frac{1}{\mu_c} \cdot \frac{l_c}{A_c} \tag{28}$$

becomes the frequency dependent, complex relation given by

$$R_c = \left(\frac{1}{\mu' - j\mu''}\right) \frac{l_c}{A_c} \tag{29}$$

and the resulting real and imaginary components of the core reluctance can be shown as

$$R_c' = \frac{l_c \mu'}{A_c[(\mu')^2 + (\mu'')^2]} \tag{30}$$

$$R''_c = \frac{l_c \mu''}{A_c[(\mu')^2 + (\mu'')^2]} \tag{31}$$

As previously stated, R' and R'' must be calculated for small segments of each cross section (Ac) and summed to obtain the total core reluctance R'_{cT} and R''_{ct}.

The gap reluctances R_{ge} and R_{gr} are not frequency dependent but purely resistive, and therefore are added as scalar quantities to the real part of the core reluctance. Thus, the total magnetic circuit reluctance, or magnetic impedance, at any specified frequency is

$$R_f = \sqrt{(R_{ge} + R_{gr} + R'_{ct})^2 + (R''_{ct})^2} \tag{32}$$

where

R_f is the complex core reluctance at any frequency
R_{ge} is the effective front gap reluctance
R_{gr} is the rear gap reluctance
R'_{ct} is the total real component of the core reluctance
R''_{ct} is the total imaginary component of the core reluctance

To obtain the head efficiency at any frequency, the complex core reluctance R_f can be substituted in the basic head efficiency Equation (20), thus:

$$\epsilon = \frac{R_{ge}}{R_f}$$

$$= \frac{R_{ge}}{\sqrt{(R_{ge} + R_{gr} + R'_{ct})^2 + (R''_{ct})^2}} \times 100\% \tag{33}$$

where ϵ is the head efficiency.

Complex Permeability Measurement To establish values for R' and R'', the values for μ' and μ'' of the complex permeability must first be determined. Some material manufacturers specify complex permeability; however, the design requirements for most video heads are so specialized that the complex permeability data must often be obtained by the designer. This may be accomplished by winding a toroidal ring made from the head core material (Fig. 44a) with N turns. The toroid is then treated as an impedance Z with a cross sectional A_c and a mean length l_c, which can be represented by the equivalent circuit shown by (Fig. 44b), consisting of an inductance L_s, a loss resistance R_1, (in the dotted area) and the dc resistance of the coil R_{dc}. To minimize leakage losses the size of the toroid dimension must be kept small (0.250 in OD, 0.125ID). A relatively large wire is used to reduce the dc resistance of the coil. The impedance Z and the phase angle can be measured with a vector impedance meter. The real and imaginary, complex permeabilities can then be determined as:

$$\mu' = \frac{\sin\phi Z l_c}{\omega N^2 A_c} \times 10^8 \tag{34}$$

$$\mu'' = \frac{(\cos\phi Z - R_{dc}) l_c}{\omega N^2 Ac} \times 10^8 \tag{35}$$

where ω is $2\pi f$
f is in Hz
l_c is in cm.
A_c is in cm^2.

Plots of μ' and μ'' with respect to frequency for typical manganese zinc hot-pressed ferrite and Alfesil (Sendust) core materials are shown by Figs. 45 and 46 respectively.

Reproduce Heads Head efficiency is of prime concern in a video reproduce head, as it determines the output voltage at all wavelengths. (The entire reproduce head function is calculated in Section 2.3). As video heads are not required to operate at wavelengths much longer than 0.003 in (0.076 mm), the contribution from flux outside the gap region is minimal, and therefore the long wavelength contour effects (see Section 2.3) are of little consequence. Because the reproduce flux levels are very low, neither pole tip nor core saturation is of concern.

Core Design Considerations To minimize the core reluctance, the magnetic path length l_c must be short and the cross sectional area A_c large, compatible with obtaining the required number of turns on the coil (see Fig. 47). In video head cores a large percentage of the flux flows close to the periphery of the coil aperture, and therefore the path length l_c is largely determined by the coil aperture (window) dimension. The head core is typically constructed in two half sections, with the gap running the entire length of the core. To minimize the effect of the rear gap reluctance, the confronting surface areas of the rear gap and front gap should be in the ratio of ten to one. Additionally, the core material should be selected for minimum losses (low μ'') and maximum permeability (high μ') for the required frequency range of the head.

Gap Length In order to maintain the gap reluctance as high as possible, the effective gap length is usually determined by the maximum gap loss (see Section 2.3) that can be tolerated by the recorder, at the shortest wavelength to be reproduced. The general rule for most applications is to select the effective gap length equal to one-half the shortest wavelength to be reproduced. Due to mechanical imperfections in the gap confronting surfaces, the effective gap is somewhat longer than the thickness of the physical spacer. The effective gap lengths for ferrite and for metal core video heads are approximately 5% and 10% longer than the physical gap, respectively.

Head Efficiency Calculation In the following example, the procedure for calculating the head efficiency and inductance of a typical video reproduce head shown in Fig. 47 is given.

1. For this example, the track width T.W. and gap length l_g for a Type C NTSC video recorder, are taken as 0.005 in (0.0127 cm) and 35 μin (89×10^{-6} cm) respectively.
2. A good estimate of the magnetic path length is approximately 0.010 in (0.0254 cm) larger than the periphery of the coil aperture, which for this example is equal to 0.318cm.
3. The various cross sectional areas for a typical video core are as follows:

$$A_c = 0.0016\ cm^2$$
$$A_{gf} = 0.000064\ cm^2$$
$$A_{gr} = 0.003\ cm^2$$

4. The front and rear gap reluctances R_{gf} and R_{gr}, may be determined from Equation 5.

$$R_{gf}=\frac{89\times10^{-6}}{0.000064}=1.39$$
$$R_{gr}=\frac{89\times10^{-6}}{0.003}=0.030$$

5. The front gap shunt reluctances may be estimated by Equations 22 and 23. Substituting the appropriate core parameters we have

$$R_{s1}=\frac{\pi}{\left[2(0051)+0.0127\right]\ l_N\ \pi\ \frac{0.1524}{[89\times10^{-6}]}}$$
$$=15.97$$

$$R_{s1}=\frac{0.524}{0.0127 l_N[0.524\frac{0.031}{89\times10^{-6}}]}=8$$

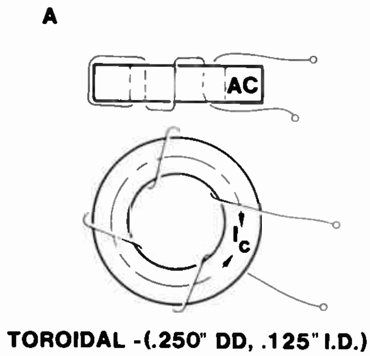


Fig. 44a Side and Top Views of Toroid

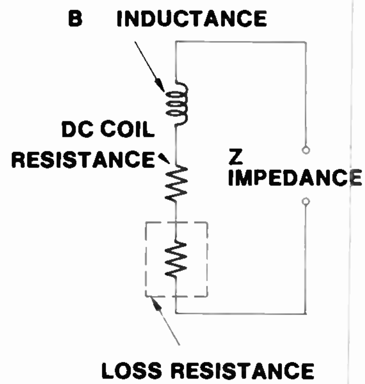


Fig. 44b Equivalent Circuit

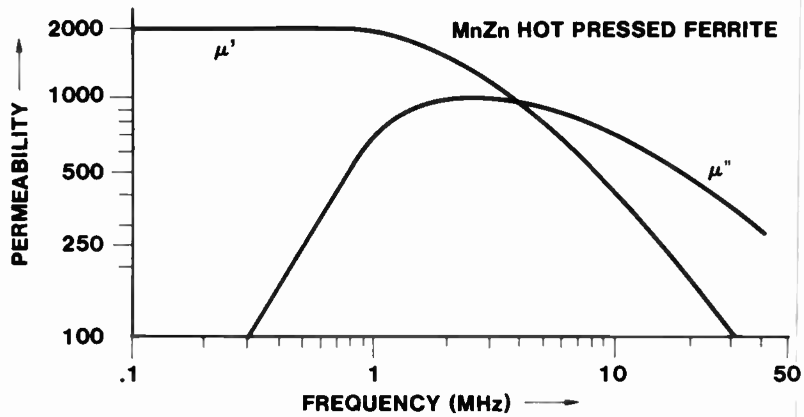


Fig. 45 Permeability vs. Frequency for Hot Pressed Ferrite

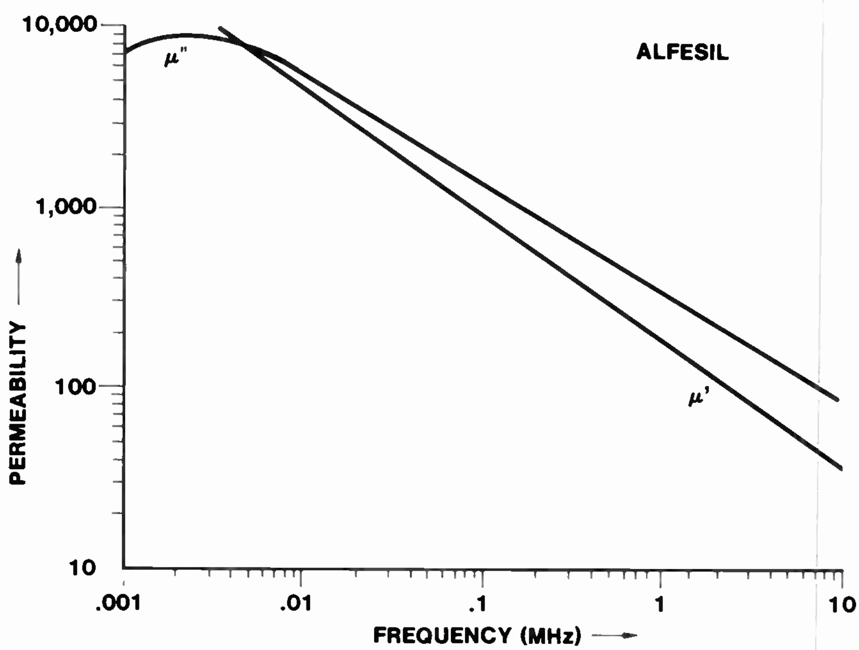


Fig. 46 Permeability vs. Frequency for Alfesil

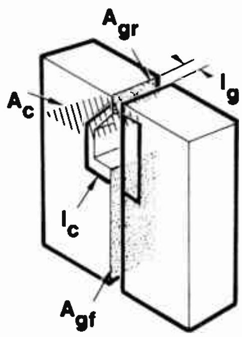


Fig. 47 Physical Parameters of Video Core

6. Calculate the total shunt reluctance from equation No. 13.

$$R_{st} = \frac{(8)\ (15.97)}{8+15.97} = 5.28$$

7. The effective front gap reluctance is obtained by using Equation No. 14.

$$R_{ge} = \frac{(1.39)\ (5.28)}{1.39 + 5.28} = 1.1$$

8. The values for μ' and μ'' are selected at the operating frequency (9.5 MHz) from the curve shown by Fig. 45.
9. The real and imaginary parts of the core reluctance are calculated by using Equations No. 30 and No. 31.

$$R'_c = \frac{0.318 \times 400}{0.0016[(400)^2+(700)^2]} = 0.122$$

$$R''_c = \frac{0.318 \times 700}{0.0016[(400)^2+(700)^2]} = 0.214$$

10. The magnetic impedance is calculated by Equation No. 32.

$$R_f = \sqrt{(1.1+0.030+0.122)^2+(0.214)^2}$$

$$=1.27$$

11. The head efficiency may now be determined from Equation No. 33.

$$\epsilon = \frac{1.1}{1.27} 100\% = 86.6\%$$

Inductance: As in the case of head efficiency, the inductance also is frequency dependent (core losses). The inductance L_f at any frequency may be obtained by substituting the magnetic impedance in the following expression:

$$L_f = \frac{0.4\pi N^2 10^{-8}}{R_f} = \frac{0.4\pi N^2 10^{-8}}{\sqrt{(R_{ge}+R_{gr}+R'_{ct})^2+(R''_{ct})^2}} \quad (36)$$

where L_f is the inductance in H, and N is the number of turns.

In the example considered,

$$L_f = \frac{0.4\pi (6)^2 10^{-8}}{1.27} = 3.56 \times 10^{-7} = 0.356 \mu H$$

Gap Depth: Assuming a video head core with a given track width (dependent on the tape format), in which the core reluctance has been reduced to the minimum possible, and the gap length established as above, the gap depth then becomes the controlling dimensions with regard to efficiency and head life. Under these conditions the gap depth is usually established by the signal-to-noise requirements of the recorder. Because of the lower wear rate of ferrite core material, the gap depth can be reduced to relatively small dimensions and still retain a reasonably high head life. Gap depth on video heads ranges between 0.00075 in (0.02mm) and 0.003 in (0.076mm), depending on the application.

Record Heads The basic design objective for a record head is that the gap field be less than the saturation induction of the head pole tip material and at the same time provide the necessary recording field above the gap to magnetize the tape at the required recording depth. Many video tape recorders use the same head for recording and reproduce. In such cases, a compromise must be struck between the optimum performance of each function. However, most professional recorders use separate heads, and both the record and reproduce functions may be optimized.

Head Field: Figure 48 shows a record head in which a signal current I is applied to a coil of N turns. As a result of this current, a gap field H_g is created across the head pole tips and is related to the gap length l_g, amp turns NI, and head efficiency ϵ by

$$H_g = \frac{.4\pi NI}{l_g}\epsilon \quad (37)$$

where

H_g is in Oersteds
I is in amps
l_g is in cm.

The gap field H_g produces a recording field H_x above the surface of the head. This field may be thought of as a bubble that emanates from the head gap to magnetize the tape. The intensity or size of the bubble relative to H_g is a function of the ratio of the gap length l_g to the recording depth y, and is expressed by the Karlquist equation for the maximum longitudinal field above the gap centerline.

$$H_x = \frac{H_g}{\pi} 2 \tan^{-1} \frac{l_g}{2_y} \qquad (38)$$

Figure 49 shows a plot of the equation in which H_g is normalized to 1.

Critical Recording Field In order to magnetize the tape, the recording field H_x must be equal to or exceed a certain critical value, which is approximately equal to the coercivity H_c of the tape at the required recording depth y. Irreversible magnetization results when the tape passes through the *record zone,* the region within the field contour line $H_x = H_c$ (Fig. 50).

Recording Depth The recording depth is usually established at $\lambda/3$, within which 90% of the available reproduce flux occurs. Typical recording depths for video recorders range from 20 to 50 microinches.

Pole Tip Saturation Pole tip saturation occurs if the gap field approaches the saturation induction B_s of the pole tip material before the required recording depth is reached. The gap edges saturate first because of the high field concentration at these points. If the record current is increased in an attempt to reach the required recording depth, the entire pole tip may become saturated. As a result of this saturation, the permeability of the pole tips will be reduced, which tends to increase the record gap length. The increased gap length reduces the gap field H_g, producing a self-limiting effect on the recording field H_x and preventing the required recording depth y from being reached. These saturation effects lower the gap edge definition, reducing the head field gradient and resulting in poor short wavelength resolution. The effects of pole tip saturation can be avoided if the gap field H_g is approximately one-half the saturation induction (B_s) of the pole tip material. (By definition, when μ = 1 (CGS), as is the case with a nonmagnetic gap, then the induction B is equal to the gap field H_g.)

Record Gap Calculations The procedure to determine the record gap length will be outlined by the following example.

1. The value for B_s for Ampex PS52B typical manganese zinc ferrite is approximately 4500 gauss. Using the factor one-half, H_g=2250.
2. The coercivity of Ampex 196 video tape is 650 Oersteds.
3. In this example the recording depth y is selected for a wavelength corresponding to the grey level carrier frequency (9.5 MHz) of a Type C video recorder, which is where the record current is optimized. Thus, record depth is
$$y = \frac{v}{3f} = \frac{1000\ ips}{3(9.5\times10^6 Hz)} = 35\times10^{-6}$$
inches.
4. The record gap l_g can now be determined by solving equation number 27 (Karlquist) for l_g. Thus,
$$l_g = 2y \tan\left(\pi \frac{H_x}{2H_g}\right) \qquad (39)$$
5. Substituting the parameter values selected in steps 1, 2, and 3,
$$l_g = 2\,(35\times10^{-6}) \tan\left[\pi \frac{650}{2(2250)}\right]$$
$$\approx 34\times10^{-6} \doteq 34\mu in$$
6. The amp turns to produce the gap field H_g can now be computed by rearranging Equation Number 37.
$$NI = \frac{l_g H_g}{.4\pi\epsilon} \qquad (40)$$
The head efficiency of the record head is determined in the same manner as the reproduce head. Thus, using the same core geometry as in Fig. 47 and the record gap length just calculated,

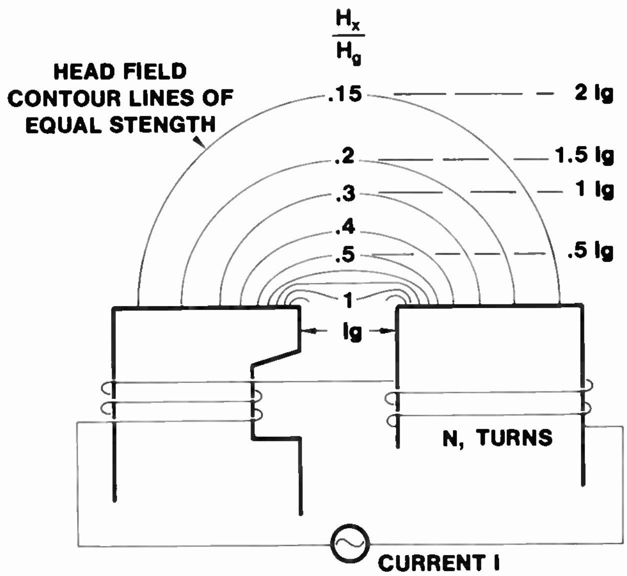


Fig. 48 Recording Field

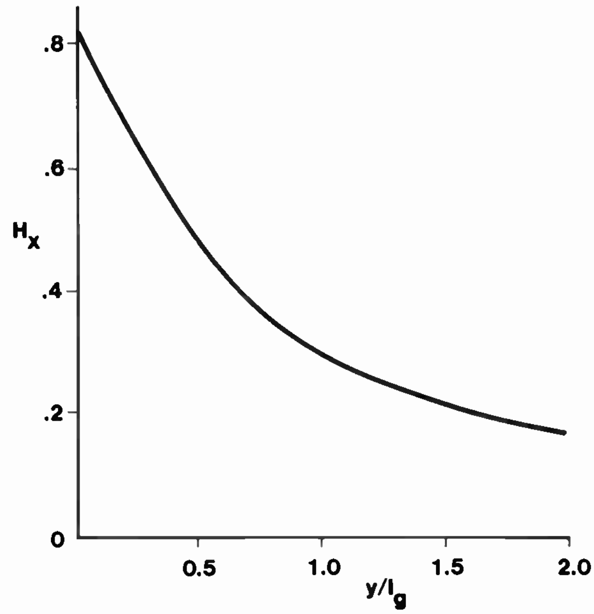


Fig. 49 Longitudinal Field vs. Recording Depth to Gap Length Ratio

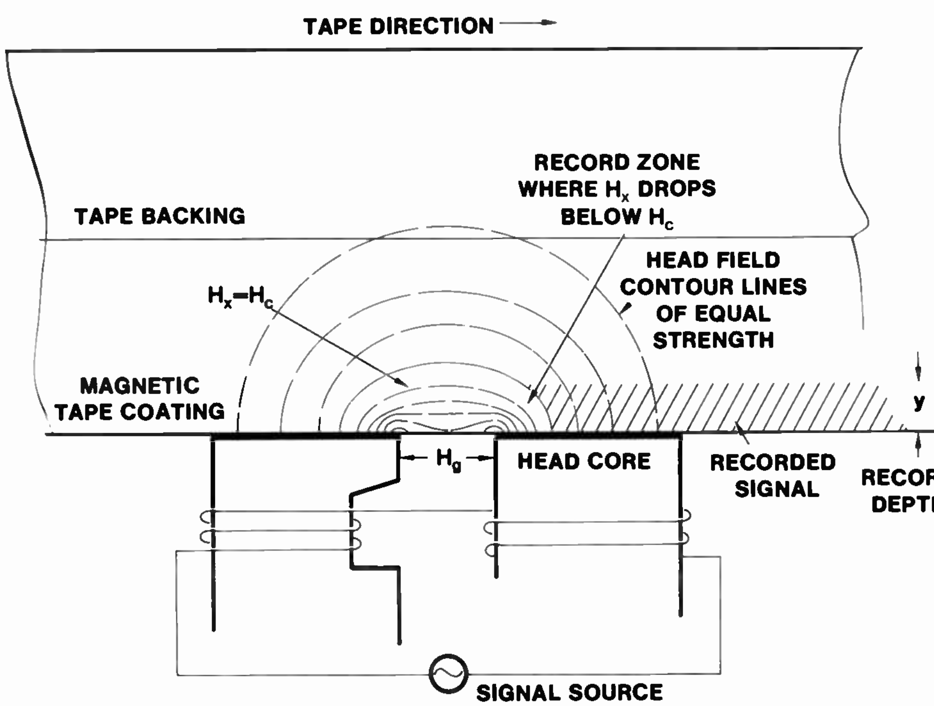


Fig. 50 Recording zone

the record efficiency is found to be 86%. Substituting the appropriate values in Equation (40), the amp turns are,

$$NI = \frac{2.54(34\times10^{-6})2250}{.4\pi 0.86} \quad (41)$$
$$=0.179\text{amp}$$

The preceding calculations for both record and reproduce head parameters provide reasonable estimates, which are adequate for the initial design; final design is ultimately determined empirically.

Record Gap Depth If for the record core the track width is determined by the format, the core reluctance minimized, and the gap length established as in the foregoing example, the gap depth again is the controlling dimension with respect to head efficiency and life.

Other Considerations To optimize the recording resolution at short wavelengths, it is necessary that the recording gap edges be sharp and straight. Additional improvement with regard to short wavelength resolution may be obtained by reducing the record gap length to improve the head field gradients. However, the gap length must not be reduced to the point that pole saturation occurs.

As the tape coercivity H_c is increased, the gap field H_g required to provide the critical recording field H_x must increase a proportionate amount. To avoid pole tip saturation effects with high coercivity tape, it becomes necessary to operate at reduced recording depths.

Video Head Construction

Metal Video Heads - History It was generally recognized that ferrites, because of their superior electrical properties at high frequencies, were better suited to video applications than the metal core materials. However, high porosity and other mechanical characteristics made it impossible to fabricate ferrite video heads that did not show rapid gap erosion under the abrasive action of the tape.

It was not until the glass-bonding and high-density ferrite technology had been perfected in the late 60s and early 70s that ferrite video heads could be made to withstand the abrasive effects of tape contact. In the early days of video recording, ferrites were mostly used to make erase heads where gap resolution was of little importance.

The early video heads were confined to metal core materials, chiefly Alfenol and Sendust (Alfesil). Alfenol was being investigated by the Office of Naval Ordinance Laboratories, and was made available for commercial applications in thin sheet form in the early 1950s. Alfenol is 16% aluminum, 84% iron, and its wear rate is approximately one-fourth (1/4) that of Permalloy. Extreme brittleness and critical heat treating were its biggest drawbacks. Sendust (Alfesil) is the most widely used metal core material for video heads. Developed in Japan in the 1950s, its approximate composition is 10% silicon, 5% aluminum, and 85% iron. However, it was not available in the United States until the 1960s. It is a vacuum-melted alloy, approximately twice as hard as Alfenol, and much less critical to heat treatment. Both Alfenol and Sendust have relatively low resistivity, resulting in high eddy current losses and low head efficiency at video frequencies. Novel designs to circumvent the losses of metal core materials have made their use possible for video head applications, some of which will be discussed briefly.

Composite Heads A novel head design (Fig. 51) that utilized the advantages of both metal and ferrite was proposed by Kornei in 1954. This was the *composite* head, so named because of the use of two different materials to make one magnetic core.

Although many constructional and manufacturing refinements have been made in the intervening years, the basic design remains unchanged and is the backbone of modern wide-band fixed gap heads. Figure 51 shows metal pole tips made from Alfenol, Sendust, or Permalloy, bonded to a ferrite core to form composite core halves. The core halves are joined with a nonmagnetic gap in the center to form the complete head core. The metal pole tips provide high gap definition, and the ferrite reduces the core losses at high frequencies, resulting in increased head efficiency. To minimize high frequency losses, the amount of metal in the pole tips is reduced to the absolute minimum, compatible with sound structural integrity. In some designs, the pole tips are also laminated to further reduce the losses. The construction of these heads requires that the mating surfaces between the metal and ferrite be lapped to a high finish and held in intimate contact to ensure a low magnetic reluctance.

One of the first video heads was a composite head designed by Pfost in 1955, and shown schematically in Fig. 52. The design consisted of two confronting Alfenol metal pole tips with a gap spacer between them and held in intimate contact with one side of a slotted ferrite ring core, with a coil connected to the signal source. The pole tips were oriented to bridge the slot in the ferrite. The slot provided a high reluctance gap in the ferrite so that the flux path was completed through the Alfesil pole tips. The various components of the magnetic core were held in the required relationship to one another by high precision mechanical parts which were assembled with screws and epoxy. A head of this type was used on the first quadruplex video tape recorder.

Another type of composite video head, developed by Pfost in 1959, is shown in Fig. 53. In this head Sendust was used as the core material and brazed together instead of being mechanically clamped. The advantage of this design over the preceding was a more rigid structure, producing better quality and longer lasting gaps. This head was constructed by brazing two Alfesil core blocks approximately 0.3 in (0.762 cm) long, in which a winding aperture had been cut. The brazed block was sliced into the individual head cores, and a ferrite core member was placed on the Alfesil core to form a composite head. A coil was wound around both the Alfesil and the ferrite cores, to complete the head. This type of structure was used in video recorders until the mid-1960s.

Noncomposite Alfesil Heads Chupity, in 1962, found that the effects of high frequency losses could be substantially reduced by using a composite brazed Alfesil core, in which the coils were placed through a very small winding aperture near the front of the head. This design brought about a large reduction in the magnetic path length, which lowered the core reluctance and resulted in a much-improved head efficiency at high frequencies. Additionally, by eliminating the ferrite member, the construction was simplified, resulting in lower cost. This design was widely used for quadruplex video recorders. Figure 54 shows a flow chart of the construction steps of a typical metal video head.

In order to facilitate batch fabrication, the head core is constructed from an Alfesil core block 0.3 in (0.762 cm) to 0.5 in (1.27 cm) long in which the required profile section has been cut by special grinding techniques. Carbide grinding wheels, along with very slow feed rates, have been found to give the best results. To obtain the gap definition that is necessary for optimum short wavelength performance, the gap confronting surfaces must be lapped flat to within 3μ" (0.076 μm). Flatness is typically measured by optical interference techniques, using monochromatic light and an optical flat. The lapping must be gentle and have low material removal rates to avoid damage to the gap confronting surfaces. The effect of such damage is reduction of the permeability of the gap confronting surfaces, in turn producing a gap length longer than the physical spacer.

After lapping, the gap confronting surfaces are vacuum deposited or sputtered with the required gap material, which is typically silicon dioxide (S_iO_2), aluminum oxide (AL_2O_3), or chrome. The core blocks are then bonded by holding them in a fixture so that the gap confronting surfaces are in intimate contact. Brazing rods coated with a flux are inserted into the brazing hole in the core blocks. The fixture and blocks are heated to the melting temperature of the brazing rod and bonded. With this technique, bonding takes place only within the brazing hole. The gap spacer is maintained by the mechanical clamping forces of the core blocks.

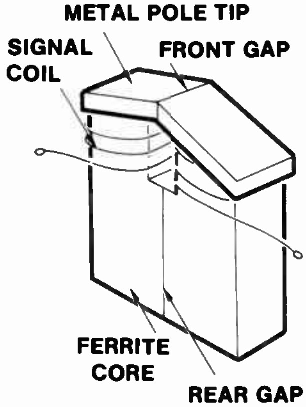


Fig. 51 Composite Head

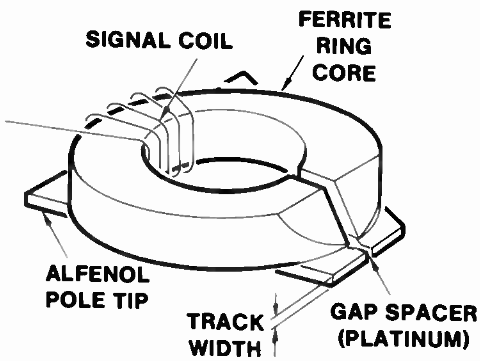


Fig. 52 Early Composite Video Head

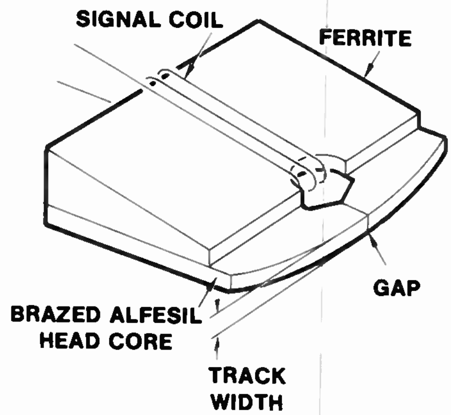


Fig. 53 Later Composite Video Head

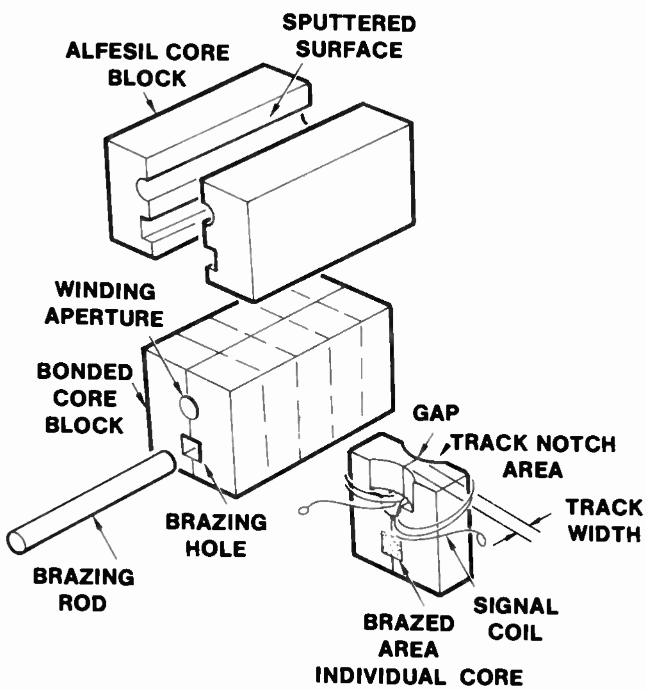


Fig. 54 Alfesil Head Construction

After the bonding operation, the bonding core blocks are sliced into the individual head cores, as shown. If the trackwidths are relatively large, approximately 0.008 in (0.02 cm) or over, the entire core area can be lapped to the track width dimensions while still maintaining sufficient mechanical strength. However, when the core thickness is reduced to below 0.008 in (0.02 mm), the strength, which is proportional to the cube root of the thickness, is substantially lowered. Moreover, the core reluctance increases and poor head efficiency results. To avoid these problems, the cores are notched to the required trackwidth dimensions in the front only. The trackwidth notch extends from the tape contact area to the aperture angle just beneath the front gap. This technique provides high mechanical strength and low reluctance.

Ferrite Heads

Hot-Pressed Polycrystalline Ferrites Ferrite materials have found wide use in video heads during the last decade, largely due to development of the hot-pressing techniques in the late 1960s. This technology made it possible to produce high density polycrystalline ferrite on a large scale. The properties of these magnetic ceramics that make them particularly desirable for video head work are hardness, high resistivity (low losses), high density, and relatively high permeability at video frequencies.

The two types of hot-pressed ferrite most commonly used for magnetic heads are referred to simply as manganese zinc or nickel zinc. Of these two types, manganese zinc ferrite is used more widely for video heads. This is primarily due to its higher saturation induction, which makes it more suited for recording on high coercivity tapes. Nickel zinc ferrites typically have higher resistivity and lower permeability. The permeability of nickel zinc is, however, more constant over a wider frequency range. Apart from the low saturation induction, the lower permeability results in reduced head efficiency relative to heads made with manganese zinc materials. Hence, the nickel zinc ferrites find little use in video heads.

Hot-pressed ferrites are made from powders of either manganese and zinc ($M_n O+Z_n O$), or nickel and zinc ($NiO+Z_n O$), mixed with an iron oxide (Fe_2O_3). After many intervening steps to process the powder, the final sintering (hot pressing) takes place in which high pressures (5000 psi) and heat (approximately 1300°C) are applied, either in one direction or isostatically.

Very small amounts (5 ppm) of oxygen can have a drastic effect on the magnetic properties of manganese zinc ferrites, and therefore the sintering must be carried out in an oxygen-free atmosphere. On the other hand, the magnetic properties of nickel zinc materials are not sensitive to oxygen, and may be sintered in air. Temperature, pressure, and time control the final grain size. Typical grain sizes range from 0.0005 in (0.0127 mm) to 0.010 in (0.254 mm).

Single-Crystal Ferrites Due to the lack of porosity, single-crystal ferrite materials offer some advantages in achieving gaps with highly defined edges. The drawback of these materials is that the magnetic and wear characteristics can vary as much as two to one, depending on the crystalographic orientation. For consistent results, strict attention must be given to the manufacturing process to ensure that the same crystalographic orientation is maintained from head to head. Single-crystal video heads have found wide use in consumer video tape recorders in recent years.

Table 4 shows the physical and magnetic properties of some typical materials used for video heads.

Ferrite Video Head Fabrication Method

Introduction Present-day ferrite material allows highly defined gap edges to be produced. However, due to the brittle nature of ferrites, the gap edges, if not adequately supported by the gap spacer material, will rapidly erode and often fail structurally when exposed to the abrasive action of the tape. A gap spacer placed in physical contact with the gap confronting surfaces, as in the Alfesil head, does not provide the ferrite material with the needed structural support

Table 4
Properties of Typical Core Materials

	Permeability μ	Coercivity Hc Oe	Saturation Induction	Resistivity	Curie Temp °C	Coeef. of Expan.
Alfesil	See Fig. 46	Approx. .06	10,000 Gauss	90 μ OHM-cm	773°	11×10^{-6} cm/cm°C
Hot Pressed Ferrite MnZn	See Fig. 45	.02-2	2000-5000 Gauss	Approx. 10-100 OHM-cm	100°-300°	$9.5-11.5 \times 10^{-6}$ cm/cm°C
Single Xtal Ferrite	Approx 300-800 at 5 MHz	Approx. .05	2000-5000 Gauss	Approx .1-10 OHM-cm	140°-250°	$9-11 \times 10^{-6}$ cm/cm°C

and protection against gap erosion. The problem of gap edge erosion was solved by the development of glass-bonding techniques. In this process a vitreous glass that approximately matches the physical properties of the ferrite materials is fused to the gap confronting surfaces, forming a monolithic structure that resists the erosive forces of the tape. In addition to providing protection for the gap edges, the glass also acts as a precision nonmagnetic spacer that controls the gap length dimension. Glass is used because it is inherently compatible with the ferrite; moreover, good adhesion, durability and wear properties that match the ferrite can be obtained. Most of the glasses used in ferrite heads are proprietary compositions that have been developed for optimum compatibility with a given ferrite material.

There are many ferrite head fabrication techniques in use today, mostly proprietary. The following descriptions of the fabrication of ferrite video heads are intended only to give an understanding of the processes involved.

Wide Track Video Head Fabrications
Two ferrite core blocks, shown in Fig. 55, are lapped to a flatness of 3 μ". In lapping ferrite material, the same precautions should be taken as for metal heads, to avoid reducing the permeability of the gap surfaces. Due to the hardness of ferrites, diamond lapping techniques are usually employed.

In the next step, the gap confronting surfaces are *sputtered* with a thin film of glass that is equal in thickness to one-half of the desired gap length dimension. *Sputtering* is a *momentum transfer deposition process*, in which an electrical discharge is set up between two plates in the presence of a low pressure inert gas, such as argon. The ionized gas atoms are accelerated by the high electric field of the glass target. These ions strike the target and release their kinetic energy, knocking off glass atoms, which in turn deposit themselves on the ferrite core block below. The thickness of the sputtered glass is controlled by the time, the pressure of the argon, and the power of the electric field.

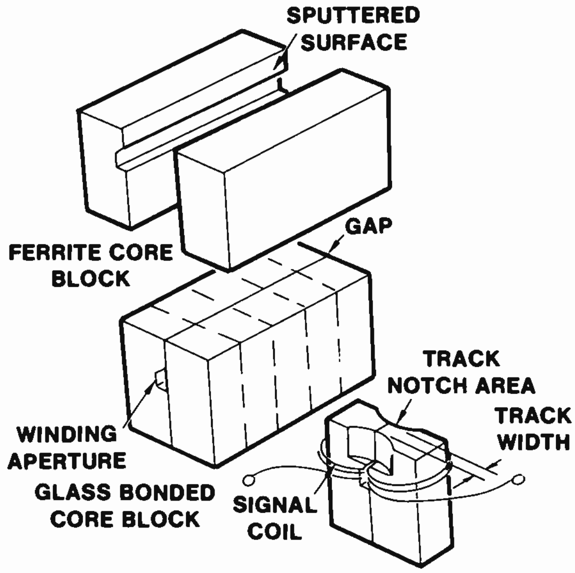


Fig. 55 Wide Track Ferrite Head Fabrication

The sputtered blocks are clamped in a fixture so that the sputtered surfaces face each other. The temperature is then elevated in an oxygen-free atmosphere to a point where the glass molecules migrate together and the core blocks are thus fused along the entire gap line. To complete the head, the bonded block is cut into separate cores, and the track width is notched. A signal coil is then wound through the winding aperture. The core is mounted on a support means and contoured to the final gap depth in the *head scanner*.

Differential wearing between the gap glass and the ferrite occurs if the wear rates of both materials are not well matched. As a result of differential wear, the gap edges will become unsupported and erosion will take place, thus degrading the short wavelength resolution.

An alternative method of glass bonding, is illustrated by Fig. 56, which shows a pair of ferrite core blocks ready to be bonded. The gap confronting surfaces are separated so that a free air space is created between them, which has the same dimensions as the desired gap length. Many techniques have been employed to create the air space to the precision required. Examples are vacuum depositing, or sputtering, small spacer strips on the gap confronting surface; precision metal foils; and cleaved mica shims. Glass in the form of rods, sheets or powders are placed in close proximity to the air space. The blocks and glass are then raised in temperature until the viscosity of the glass is low enough to be drawn into the air space by capillary action. Adhesion takes place between the gap confronting surface and the glass, bonding the core blocks. A drawback to this process is that at small gap lengths (below 50μin, or 1.27μm) the glass does not always fill the air space, and *inclusions* result, giving rise to poor manufacturing yields. This technique has found wide use in the fabrication of computer disc heads, where the gap lengths are usually in excess of 50μin.

Narrow Track Heads The track notching technique described previously is adequate to produce relatively wide track video heads. However, when he tracks are reduced to 0.003 in (0.076 mm) or smaller, the notched area becomes very fragile and prone to breakage. To overcome this problem, the notched areas are filled with glass to support the trackwidth on each side. The support glass is fused to the ferrite, greatly increasing the structural integrity of the track notch area. Additionally, the glass pockets isolate the track and reduce the edge chipping. Using the technique allows extremely small tracks (below 0.001 in, or 0.025 mm) to be manufactured. Most home video recorders use heads of this type. An example of the basic fabrication steps of a glass-notched video head is illustrated by Fig. 57.

The track width is defined by the land area between a series of small notches that are cut along the length of the ferrite core block. Next, the notches are filled with glass, and the gap confronting surfaces of the core block are lapped and sputtered with glass. The individual head cores are produced by cutting along the center of the glass-filled areas. The heads are completed in the matter outlined earlier.

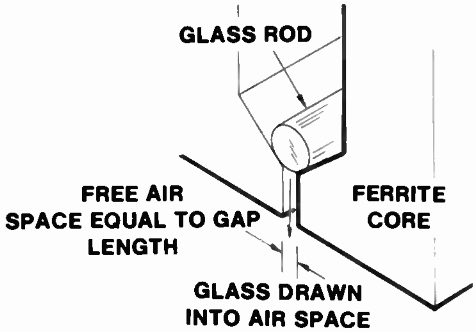


Fig. 56 Capillary Bonding Technique for Ferrite Heads

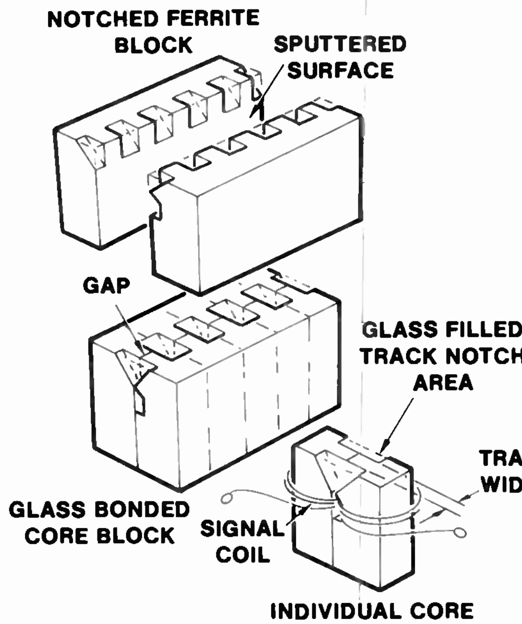


Fig. 57 Narrow Track Ferrite Head Fabrication

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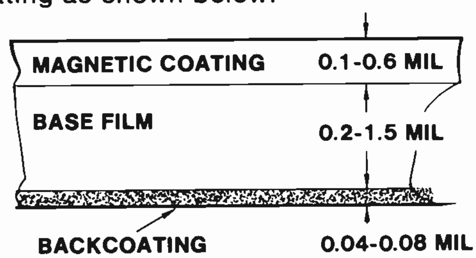
3. MAGNETIC TAPE

Robert H. Perry

Magnetic tape includes a multiplicity of products used for magnetic recording, all consisting of a magnetizable medium on a flexible substrate. Because of the great variety of machine types and recording formats in use and being developed, magnetic tape is designed and produced with widely different magnetic media, widths, thicknesses, lengths and other properties optimized for each application. Media are used either in strip form in reels, cartridges, cassettes and cards, or in disks of different diameters. Similar technology is used to produce all of these products. They represent a high-technology industry, and the highest standards of quality and precision are maintained in the selection of raw materials, in the product design, and ultimately in the manufacture, testing and packaging of the products. This chapter is a brief description of magnetic tape and how it is made.

3.1 CONSTRUCTION Magnetic tape consists of three components: a magnetic film or coating supported by a flexible substrate, or base film, which in many applications is coated on the back side by a non-magnetic coating as shown below.



Magnetic Tape Base Film and Coating Thicknesses

Backcoating Backcoatings are used primarily in the most demanding tapes, such as professional and some consumer video, professional audio, instrumentation and data products, where special winding and handling characteristics are required. This coating contains a conductive pigment, usually carbon black, which reduces buildup of static charge and therefore minimizes the accumulation of dirt and debris on the tape, factors which can cause dropouts, or loss of signal with attendant loss of stored information. The backcoating also provides better frictional characteristics than raw base film does, and air is more easily eliminated from adjacent layers during winding. This reduces the tendency of the tape to *cinch* or form *pop strands*, and there is less likelihood of uneven stacking, edge damage and creasing of the tape.

Base Film The base film is an integral and significant part of the whole tape system and is largely responsible for its mechanical strength and stability. Other factors such as stiffness and surface smoothness have a profound influence on tape performance in many applications, and base films having the proper characteristics for a given application must be carefully selected.

The principal substance used in the great preponderance of magnetic tapes today is poly(ethyleneterephthalate), or simply *polyester*, abbreviated PET. PET has an excellent combination of properties including chemical stability, mechanical properties, such as tensile strength, elongation and modulus, tear resistance, availability and cost. Some typical properties are shown in Table 5.

Many different types and grades of PET are on the market for both magnetic tape-related and unrelated applications. In all cases mechanical strength in the plastic film is achieved during its manufacture by a process of biaxial and sometimes uniaxial orientation of polymer chains in the hot film after extrusion of the melt. Biaxial orientation is achieved by stretching in both the machine and the transverse directions, and the resulting film has a balance of properties in the two directions. Balanced film is adequate for many magnetic tape applications, especially those employing gauge thicknesses greater than 0.5 mil. In thinner gauges greater resistance to stretching is needed, and PET is used which is *tensilized*, i.e., oriented by drawing additionally in the machine direction.

Table 5 Physical Properties of Poly(ethyleneterephthalate)*

Property	Balanced	Tensilized
Tensile strength, psi	25,000	40,000
Force to Elongate 5%, psi	14,000	22,000
Elastic Modulus, psi	550,000	1,100,000
Elongation, %	130	40
Thermal Coefficient of Linear Expansion, per °C	1.7×10^{-5}	1.7×10^{-5}
Shrinkage at 100°C % (@ 30 min.)	0.4	2.5

*Measurements in machine direction

Base films for magnetic tape range in thickness from about 0.2 mil to 1.5 mils (3 mils for flexible disks). They are employed by tape manufacturers in widths ranging from 12 in to 60 in and in lengths up to 15,000 ft. The base film manufacturer must ensure that the base film has the right balance of surface smoothness for recording performance and roughness for runnability in the coating and processing steps. Small-particle-size, inorganic additives are incorporated in the PET to provide slip properties in film that would be otherwise unmanageable. These surfaces asperities must be critically controlled especially for short-wavelength recording applications, since the base film surface roughness profile can to a degree be carried through the magnetic coating and reflected in the tape surface roughness. An asperity of 10 μin, for example, in a typical, 100 μin wavelength video recording can result in a loss of signal of 5.5 dB due to head-to-tape separation, as seen from the Wallace formula:

$$\text{spacing loss, in dB} = 54.6\ d/\lambda$$

where d is the head-tape spacing and λ the wavelength.

3.2 MAGNETIC COATING There are two types of magnetic coatings used in magnetic tape. Most of them use magnetic particles bound in a matrix of organic, polymeric binder that is applied to the substrate from a dispersion in solvents. To a limited extent, other types are made by vapor deposition of thin films of metal alloys, and this is an area in which much development work is in progress.

Most magnetic coatings contain a single layer, although there are a few tapes made with dual-layer magnetic coatings having different coercivities, and are designed to have flat response over a range of frequencies. Magnetic tape performance is a function of both the formulation of ingredients in the coating and the process by which the coating is applied and processed. The most important component in the formulation is the magnetic material.

Magnetic Materials A wide variety of single-domain magnetic particles is used having different properties depending on the electrical requirements of each tape application. Retentivities range from about 1000 to 3000 gauss, and coercivities range from about 300 to 1500 Oe. Size and shape are important since they relate to how well the particles pack in the coating; the signal-to-noise ratio achievable is proportional to the number of particles per unit volume in the coating. The length of the particles is about 8-40 μin (0.2-1.0μm), and they are acicular with aspect ratios of 5:1 to 10:1. Acicularity makes the particles magnetically anisotropic, and thus it governs magnetic properties not inherent in the material. In general, magnetic pigments are loaded to as high a level as possible commensurate with retention of desirable physical properties and avoidance of shedding. The limiting factor is the amount of pigment the binder can retain without loss of cohesion and hence durability.

There are four types of magnetic particles used in magnetic tape: γ-ferric oxide, doped iron oxides, chromium dioxide and metallic particles that usually consist of elemental iron, cobalt and/or nickel. γ-Ferric oxide has been by far the most widely used material (Hc 300-360 Oe) and is useful for many of the lower-energy applications in which the ultimate in recording density or short-wavelength recording capability is not required. The sequence of steps used in the commercial production of γ-ferric oxide is as follows: precipitation of seeds of α-FeOOH (goethite) from solutions of scrap iron dissolved in sulfuric acid, or from copperas (ferrous sulfate obtained as a by-product from titanium dioxide manufacture); growth of more goethite on the seeds; dehydration to $\alpha-Fe_2O_3$ (hematite); reduction to Fe_3O_4 (magnetite); and oxidation to γ-ferric oxide (maghemite). An improved γ-ferric oxide is produced starting with ferrous chloride rather than ferrous sulfate and precipitating γ-FeOOH (lepidocrocite) rather than α-FeOOH in the initial step.

Cobalt doping of iron oxide affords particles with higher coercivities (500-1200 Oe). The older process involves precipitation of cobaltous salts with alkali in the presence of yellow iron oxide (α- FeOOH), dehydration, reduction to cobalt-doped magnetite, and oxidation to cobalt-doped magnetite containing varying amount of FeO. The resulting particles have cobalt ions within the lattice of the oxide, and they exhibit a marked magnetocrystalline anisotropy. This gives rise both to a strong temperature dependence of the coercivity and to magnetostrictive effects, which can cause problems of greatly increased print-through, increased noise and loss of output from stress on the tape through head contact. Somewhat improved stability has been achieved by using other additives, such as zinc, manganese or nickel, with cobalt.

In recent years, epitaxial cobalt-doped particles have been developed which have largely overcome these problems because cobalt ion adsorption is limited to the surface of the oxide. Epitaxial particles have superseded lattice-doped particles in most applications.

Chromium dioxide provides a range of coercivities similar to that of cobalt-doped iron oxide (450-650 Oe) and possesses a slightly higher saturation magnetization, i.e., 80-85 emu/g compared to 70-75 emu/g for γ-ferric oxide. It has uniformly good shape and high acicularity and lacks voids and dendrites, factors which undoubtedly account for the excellent rheological properties of coating mixes made with it. Its low Curie temperature (128°C) has been exploited in thermal contact duplication, a process which was largely developed in the late 1960's but because of problems in obtaining high-quality duplicates has not been commercialized. New machine designs have resolved the earlier problems, and commercial, thermal contact duplication of chromium dioxide tape at 50-100 times real time appears to be on the horizon.

A disadvantage of chromium dioxide is its abrasiveness, which can cause excessive head wear. Also, it is chemically less stable than iron oxide, and under conditions of high temperature and humidity it can degrade to non-magnetic chromium compounds, resulting in loss of output of the tape. Chromium dioxide and cobalt-doped iron oxide yield tapes having 5-7 dB higher S/N ratio than those made from γ-ferric oxide.

Metallic particles give tapes which have 10-12 dB higher S/N ratio than those made from γ-ferric oxides as a result of their having much higher saturation magnetization (150-200 emu/g), retentivity (2000-3000 gauss), coercivity (1000-1500 Oe), and smaller particle size. These factors, together with a square shape of the hysteresis loop, permit recording at shorter wavelengths with less self-erasure. Thus, recordings can be made at slower speeds without sacrifice in dynamic range, and higher bit packing densities are possible.

Metallic particles are made by several different kinds of processes, the more important commercial ones being reduction of iron oxide with hydrogen and chemical reduction of aqueous ferrous salt solutions with borohydrides. Metallic particles are more difficult to disperse than iron oxides because of their smaller size and higher remanence, and they are highly reactive. Processes such as partial oxidation of the surface or treatment with chromium compounds are used in their manufacture to stabilize them for handling during tape manufacture. The corresponding tapes are more stable, but their susceptibility to corrosion at elevated temperature and humidity is a disadvantage.

Magnetic tape manufacturers are also developing and beginning to introduce tapes consisting of thin films (1000-1500 Angstroms) of metal alloys deposited on the substrate under vacuum or by sputtering. The retentivity of these tapes (1.2×10^4 gauss) is almost an order of magnitude higher than that of γ-ferric oxides, with a corresponding increase in recording density.

In other areas, research is being devoted to very small, isotropic particles, which have aspect ratios of 1:1 to 2:1, because of advantages which can be taken of magnetization vectors in more than one direction, i.e., vertical as well as longitudinal recording, and because of the increased number of particles that can be packed in a coating per unit volume. New particles having the shape of rice grains are used in some new tapes recently introduced and will undoubtedly find increased application in the next few years.

Binders Binders must be capable of holding the magnetic pigment together in a flexible film which adheres to the base film with a high degree of toughness and chemical stability, and with thermoplastic properties enabling the pigmented film to be compacted to give smooth surfaces. It should also be soluble in suitable solvents. These requirements are not met by many substances available today for producing state-of-the-art magnetic tapes.

Polyurethanes, either used as such or prepared *in situ*, represent the most important class of polymers for this purpose because of their affinity for pigments, their toughness and abrasion resistance, and their availability in soluble forms. Of the two types in use, poly(esterurethanes) are preferred over poly(etherurethanes) because of their superior poly(esterurethane) are shown in Table 6.

Table 6 Physical Properties of a Poly(esterurethane)

Tensile Strength, psi	8000
Stress at 100% Elongation, psi	300
Ultimate Elongation, %	450
Glass Transition Temperature, °C	12
Hardness, Shore A	76
Density, g/cc	1.17
Viscosity at 15% Solids/Tetrahydrofuran, cps	800

Other polymers may be used alone or in combination with one or two other polymers to obtain the desired properties. Although a great many types are described in the patent literature, the other most important polymers include poly(vinyl chloride-co-vinyl acetate/vinyl alcohol), poly(vinylidene dichloride-co-acrylonitrile), polyesters, cellulose nitrate and phenoxy resin.

Most modern magnetic tape coatings are crosslinked with isocyanates to provide durability. Isocyanate curing chemistry is rather complex and difficult to control, and for this reason the industry is researching an emerging new technology involving curing with electron-beam radiation. A whole new field of binders is being developed for this purpose which polymerize extremely rapidly to high polymers in a much more controllable fashion.

Dispersants Dispersants are surface-active agents which aid in the separation of magnetic particles, a process necessary for achieving the desired electrical performance of the tape (See Dispersion). They facilitate separation of charges on the particles and stabilize particle separation. Common dispersants are lecithin, organic esters of phosphoric acid, quaternary ammonium compounds, fatty acids and sulfosuccinates.

Conductive Agents Conductive materials are often added to tape formulations to reduce electrostatic charge buildup on tape as it is run on machines. Conductive carbon blacks are commonly used to reduce the resistivity of tape by about four to six orders of magnitude, from $10^{10}\Omega/sq$ or higher.

Lubricants Lubricants are necessary to prevent stiction of the tape as it comes in contact with the record or playback head. A great many different materials are effective as lubricants, including silicones; fatty acids, esters and amides; hydrocarbon oils; triglycerides; perfluoroalkyl polyethers; and related materials, often from natural products. Lubricants may be either incorporated in the tape coating formulation or added topically at the end of the tape process.

Miscellaneous Additives Small amounts of other materials are included in many tape products to achieve special properties. For example, fine-particle alumina, chromia or silica are often added to prevent debris obtained during use of the tape from accumulating on the heads and clogging them. This is not normally a requirement in tapes containing chromium dioxide as a magnetic pigment. Other additives include fungicides, which are used in certain limited applications.

Solvents Solvent choice is determined by chemical inertness, binder solubility and mix rheology, evaporation rate, availability, toxicity, ease of recovery, and cost. The most commonly used solvents for magnetic tape processes are tetrahydrofuran, methyl ethyl ketone, cyclohexanone, methyl isobutyl ketone and toluene. Many common types of coating defects can be avoided by the combinations of solvents to provide differential evaporation rates from the coating during the drying process. Finished tape normally has very low levels of residual solvent.

3.3 MANUFACTURING PROCESS The following sequence of steps is employed in manufacturing the tape: mix preparation; dispersion, or milling; coating; drying; surface finishing; slitting; rewind and/or assembly; testing; and packaging.

Dispersion The magnetic particles must be deagglomerated without reducing the size of individual particles. This step is accomplished by agitating the combined ingredients as a wet mix in one of several types of mills, such as pebble, steel ball, sand, or Sweco, which produce high shear between agglomerates. Milling efficiency in a given system is controlled by mix solids content, viscosity, mix-to-media ratio and temperature. The end point is reached when visual examination of a drawdown sample under magnification shows the absence of agglomerates or that it meets a predetermined standard of dispersion quality. Another method is to mill until a maximum in the derivative of the B-H loop is attained. Some commercial dispersion testers are available based on DC noise measurements.

Coating The coater is perhaps the most critical processing step in the entire operation. There are trade-offs between advantages and disadvantages among the different types of coating methods used, principal among which are *reverse roll* and *gravure* (Fig. 58). *Reverse roll* is the most widely used, general-purpose method; *gravure* is especially suited for very thin coatings (0.2 mil or less). *Knife coating,* one of the oldest methods, is gradually disappearing with the advent of thin coatings on thin films and high-speed, precision coatings, generally. *Extrusion* and *curtain* coating are becoming increasingly important by affording high-quality coatings at high speeds. Coaters vary in width from 12 inches to 60 inches, as do the base films, and operate at speeds of approximately 250-1000 ft/min.

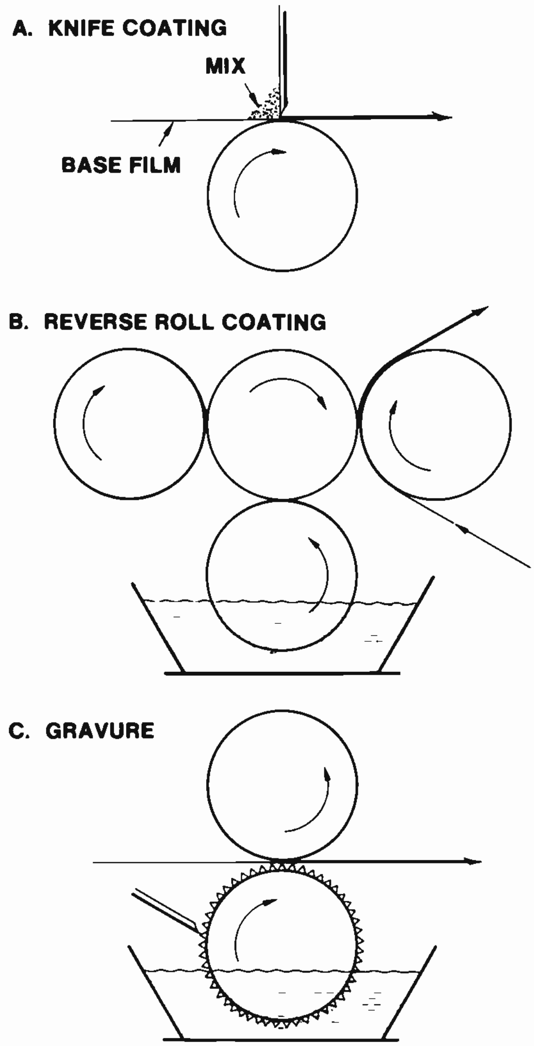


Fig. 58 Typical Coating Methods

Orientation Maximum signal-to-noise ratio is obtained when the magnetic particles are aligned, before drying, to the maximum extent possible in the direction of the intended recording. Accordingly, immediately after the wet coating mix is applied, the web is passed through the field of an orienting magnet having a field strength (500-2000 gauss) optimized for the particular magnetic particle being used. Most tapes are longitudinally oriented, although some are oriented transversely to some degree for quadruplex rotary-head video recorders, in which the recording is in the transverse direction. The coater itself exerts shearing forces on the mix and thus often imparts some longitudinal orientation in the particles even in this stage.

Drying The web is next passed through an oven containing circulating forced hot air. Many modern oven designs use air bearings at web turnaround points to avoid rubbing between plastic and metal surfaces and minimize the formation of abrasion products, which can cause dropouts. Once the coating is dried, the magnetic particles are no longer free to move. During the eventual recording process, only magnetization vectors, or aligned spins of electrons within the molecular species of the particle domains, rotate.

Surface Finishing Surface finishing is generally required to produce an extremely smooth surface to maximize head-to-tape contact, an absolute necessity for short-wavelength recording. This is accomplished by calendering the tape, or passing the web one or more times through a *nip*, or line of contact, between a highly polished metal roll and a plastic or celluosic compliant roll. This compaction process also reduces voids in the coating and increases the magnetic pigment volume concentration and in turn the retentivity of the tape.

Slitting The web is slit into strands of the desired width, from 150 mils to 3 in. Tolerances in width variation are about ± 1.0 mil for most tapes except consumer 1/2" video, for which the tolerance is considerably tighter. Edge weave, or width waviness *(country laning)* over extended length, should not vary more than about 1 to 2 mils in 1" video tapes and 0.4 mil in video cassette tape. Tape must be free from jagged edges and debris. Additional tape cleaning processes are sometimes used to ensure that loosely held dropout contributors are effectively removed.

Testing Sophisticated magnetic tape manufacturers test every component of tape in every step in the process, from individual raw materials thorough packaging. The most exacting specifications are set forth and followed. Electrical tests, including those for dropouts, are especially stringent, and in professional audio, instrumentation, video and computer tapes, each reel of tape is tested, in some cases end to end, before shipment. In addition, warehouse audits are performed to ensure maintenance of quality.

Assembly and Packaging Tape is assembled in various formats but mainly in reels, pancakes, cassettes and cartridges of different sizes. A description of processes by which these components are made and assembled is beyond the scope of this chapter. However, the same standards of precision, cleanliness and quality exist in these areas as in tape making per se, and final assemblies of tape components and packages are all performed in ultra-clean-room environments.

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4. TYPES OF VIDEO TAPE RECORDERS

Charles P. Ginsburg

In the early 1950's, when efforts to record television programs on magnetic tape began in earnest, methods for solving the problem could be classified as those which used stationary video heads, pulling the tape past them at a speed between 100 i/s and 360 i/s, and those which used rotating video heads. Many different kinds of stationary head methods were investigated. Some were straight-forward, single-video-track techniques; some used frequency or time-division multiplexing; and at least one used one type of signal handling method for the lower video frequencies and another for the higher ones. At the time of this writing, no stationary-head approach to recording television programs has met with commercial success; the technology used in the attempts to successfully develop a stationary-head television tape recorder had little to do with the technology developed for rotary head methods; and therefore no treatment of this general approach to recording television on tape will be made.

Numerous types of rotating head video tape recorders have been investigated, but only three will be described; one because of its historical significance, another because it dominated the broadcast scene for two decades, and the third because versions of it had taken over markets ranging from consumer to broadcast by the late 1970's.

4.1 ARCUATE SWEEP The *arcuate sweep* configuration, (Fig. 59), used four heads mounted so that their tips protruded about 0.003 in above the plane surface of a drum rotating at 240 rps. With a rotational velocity of 1700 ips, the heads recorded arcuate tracks across a two-inch wide tape, guided to be in contact with the heads as they described descending arcs. With a reel-to-reel tape speed of 30 ips, the recorded tracks were distorted slightly from circular shape, because the effect of the 30ips component on the relative velocity between heads and tape varied during each head sweep. The arcuate sweep technique was chosen initially to avoid the effect of the impact of heads coming into contact with the edge of the tape at right angles. However, timing errors unique to the arcuate method brought about a change in the scanning method in late 1954.

4.2 TRANSVERSE SCAN The *quadruplex,* or *transverse scan* configuration which followed, (Fig. 60), also used a two-inch wide tape. A head drum 2.064" in diameter had four heads mounted on it with their tips protruding about 0.002" past its periphery. With a rotational rate of 240 rps for 60 Hz television systems, the video head writing speed was 1550 ips. (For 50 Hz systems, these values were 250 rps and 1600 ips.) The video tracks were 0.010" wide, the reel-to-reel tape speed was 15 ips, and the *guard band* between tracks was 0.005". In recording, after the tape had passed the rotating head assembly (described in detail in Section 6.1), stationary erase heads erased portions of the tape edges, for the recording of auxiliary information, which included control track, program audio, cue track, and later, time code. The same video heads were used for both record and playback.

The quadruplex recorder was first shown at the annual convention of the National Radio and Television Broadcasters in 1956. These recorders went on the air later that year and dominated the broadcast industry for the next two decades. The format for signals recorded as the quadruplex standard is shown in Fig. 61.

4.3 HELICAL VTRs A profusion of *helical wrap* recorders has made its appearance since 1961. They all have in common the characteristic that the tape is wrapped about the *scanning assembly* in a helix, resulting in a recorded track that describes

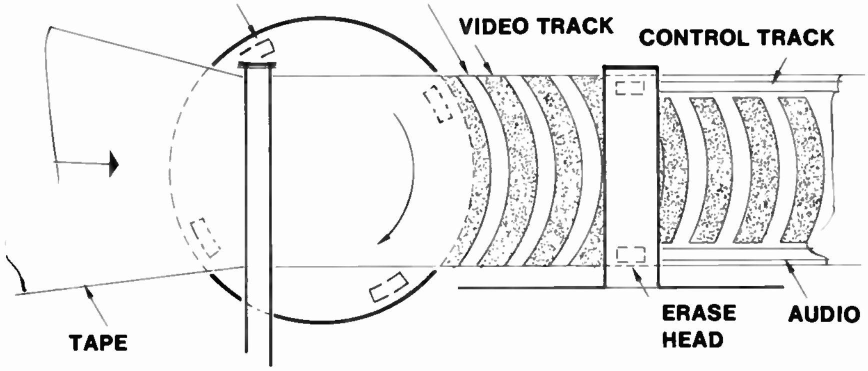

Fig. 59 Acruate Sweep Configuration

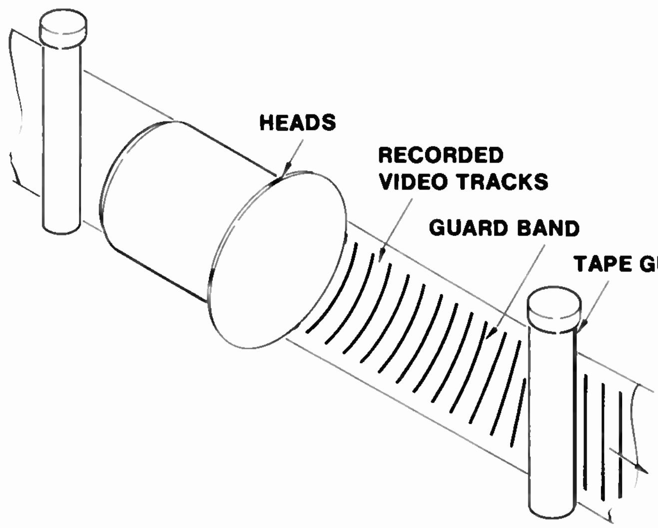

Fig. 60 Transverse Scan Configuration

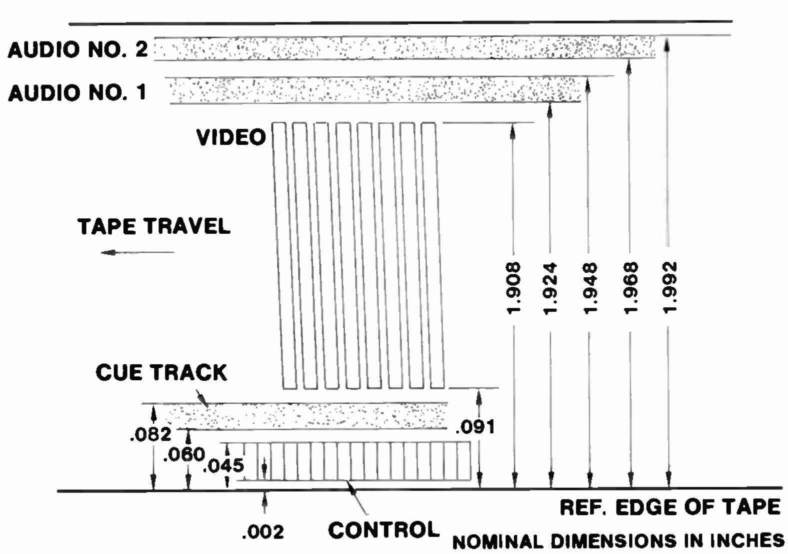

Fig. 61 Quadruplex Format

a straight, slanted line across the tape. Helical recorders may be classified as *full wrap* and as *half wrap.* Alternatively, they may be classified as *field-per-scan*, or as *segmented field*, (Fig. 62). The field-per-scan recorders write, or read, one complete field with each head pass. The segmented field recorders require several head passes, generally five or six, depending on the television system on which the recorder is operating, to write or read one field. Since 1978, the broadcast version of the one-inch segmented-field helical video tape recorders has been manufactured in accordance with the standard for the Type B format, and the one-inch field-per-scan recorders have conformed to the standard for the Type C format. These standards were established by the Society of Motion Picture and Television Engineers to make possible the interchange of tapes recorded on machines of a given standard made by different manufacturers.

Although helical recorders found wide application in industrial and commercial markets in the second half of the decade of the 1960's and beyond, and in the consumer market beginning in the early 1970's, their use in broadcasting was extremely limited. The problem was one of excessive timebase instability for on-air use. This was finally solved after the introduction of *digital time base correction* in 1973, making it possible to incorporate far wider windows in time base correctors than was practical in analog correctors. The big timing errors characteristic of most helical recorders were now under control.

Next, the development of a method for servoing the video heads themselves to permit slow-, stop-, and reverse-motion effects in certain helical recorders, coupled with a substantial decrease in operating costs through a reduction in tape costs by a factor of two-thirds compared to the transverse scan recorders, finally brought to an end the dominance of the quadruplex recorders. The reduction in the amount of tape used per unit time was the result of continuous improvements in the quality of both heads and tape. When the quality of signals played back from quadruplex recorders became so good that the track width, or even the writing speed, could have been reduced, the standard for those recorders was so firmly entrenched that a change in either was not considered practical by most users. However, the improvements were exploited in the design of the helical recorders. In 1982, the manufacture of quadruplex recorders was less than two percent of the total number of videotape recorders turned out for the broadcast market.

The formats for both Type B[2] (segmented) and Type C[3] (field per scan) recorders are shown in Figs. 63 and 64.

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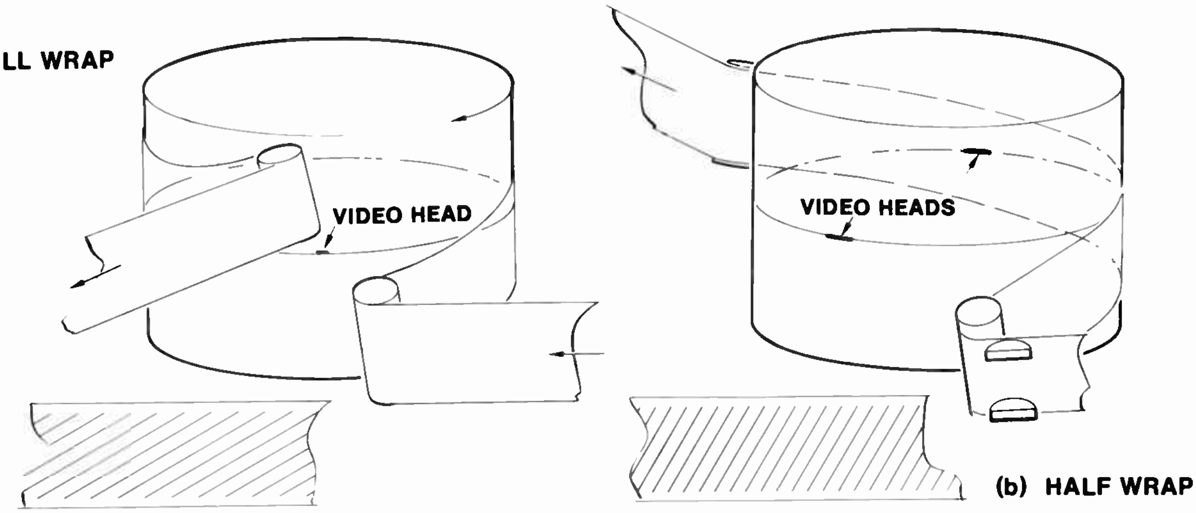


Fig. 62 Helical Configurations and Video Track Patterns

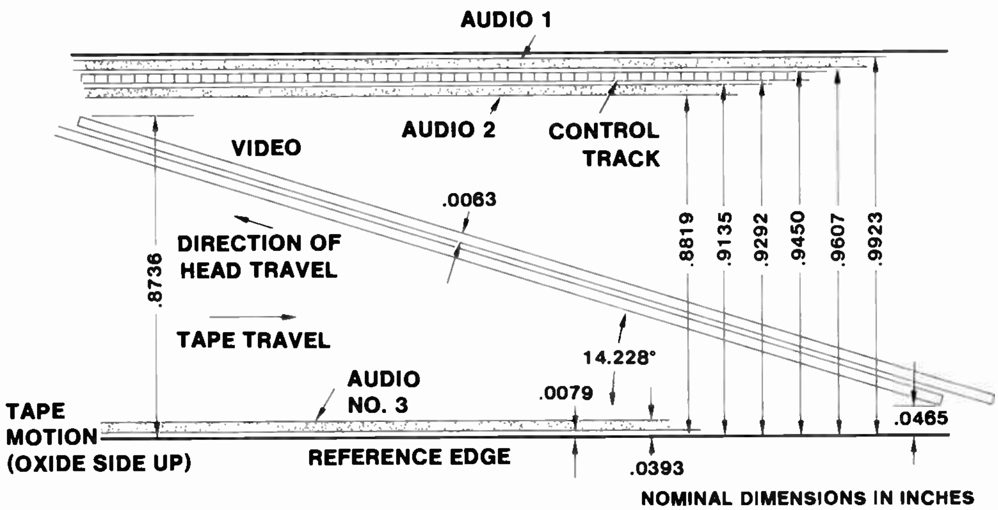


Fig. 63 Type B Format

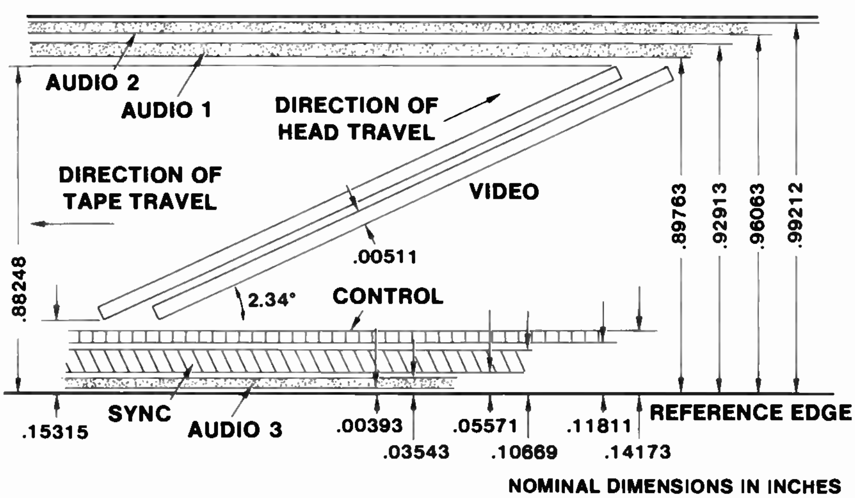


Fig. 64 Type C Format

5. SIGNAL SYSTEMS & PROCESSING

Michael O. Felix, William McSweeney

5.1 THE NEED FOR A MODULATION SYSTEM (Felix) As shown in Section 2., any magnetic recorder has a bandpass characteristic with a null at DC and a rapidly falling characteristic at high frequencies. Since the spectrum of a TV signal extends from DC to 5 or 6 MHz, it is impractical to record it without modulation. Three forms of modulation can be considered: pulse, amplitude, and frequency (or its related phase). Pulse modulation systems involve high bit rates and until recently their use was impractical. Now, however, their use appears technologically feasible.

The selected modulation system preferably should provide a demodulated noise spectrum which complements that of the response of the human eye. The eye is sensitive to large area (low frequency) disturbances (Fig. 65); it is much less sensitive as the frequency increases, except where the effects of noise close to the color subcarrier are considered. The optimum SNR is thus the same curve.

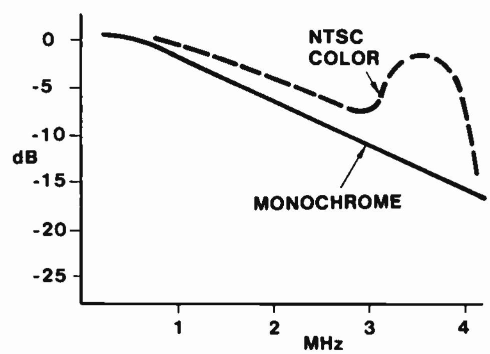


Fig. 65 Sensitivity of the eye to Noise

At first sight, amplitude modulation appears usable. By placing the carrier on the upper band edge (Fig. 66) a single sideband system of adequate bandwidth results. However, such systems are excessively sensitive to head-to-tape spacing. In accordance with the playback head to tape separation loss of $54.6\left(\frac{a+a_t}{\lambda}\right)$ dB as described in Section 2.3, with a carrier of 9 MHz and a head-to-tape speed of 25 m/sec, the playback signal decreases 1 dB for every 0.05 microns of separation. Tape surface roughness alone is of this order, since much smoother tape will cling to any polished surface, such as a tape guide. Thus the carrier-to-noise ratio of an AM system is poor, and since the noise power is essentially constant with frequency, the demodulated signal contains large amounts of the low frequency noise to which the eye is so sensitive.

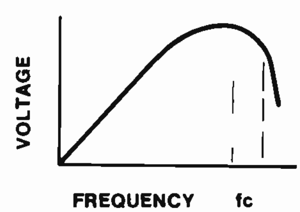


Fig. 66 Carrier on Upper Band Edge

Losses due to head-to-tape spacing have the property that variations in them produce no time jitter. Consider an isolated magnetized point on a tape (Fig. 67); whether the tape is close to the head, or far from it, the maximum flux links the head at precisely the same moment. An FM system using the same carrier frequency shown in Fig. 66 is therefore unaffected by head-to-tape spacing until the carrier-to-noise ratio falls below the FM threshold. In addition, the noise triangulation characteristic of an FM system, in which the noise increases with increasing frequency in the demodulated baseband results in a SNR variation with modulation frequency that closely matches the lower half of the curves in Fig. 65. To reduce high frequency noise, which is particularly important in color systems, the video signal is pre-emphasized before being fed to the frequency modulator; typical values provide an 8 dB boost at frequencies above 1 MHz.

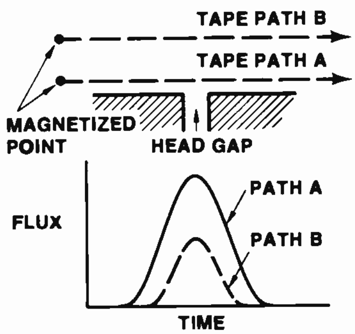


Fig. 67 Independence of timing From Head/Tape Spacing

5.2 The FM SYSTEM A frequency modulated signal can be analyzed either using a quasi-stationary approach or a sideband approach. To use the latter, consider the FM signal $v = V \sin(\omega t + \beta \sin mt)$ where ω is the carrier frequency, m the modulation frequency, and β the peak phase deviation in radians. The peak frequency deviation is then $(m\beta)$ Hz. Bessel showed that this could be split into an infinite number of sidebands, spaced m Hz apart above and below the carrier. Tables of Bessel functions can be found in any mathematical handbook; for a given β, they give J_0 (the carrier amplitude), J_1 (the amplitude of the first sidebands on $(\omega+m)$ and $(\omega-m)$; J_2 (the amplitude of the second sidebands on $(\omega+2m)$ and $(\omega-2m)$), and so on.

The FM systems found in VTR's differ fundamentally from those found in other parts of the communication industry in two respects: (1) the carrier frequency is not greatly higher than the highest modulating frequency; and (2) the deviation ratio $\beta = \frac{\Delta f}{f_m}$ is not nearly so high as for other FM systems. In a VTR the highest modulation frequency is around 5 MHz, and carrier frequencies are in the 8 to 10 MHz range. In the following discussions an 8 MHz carrier modulated by a 4.4 MHz sinewave (approximately the frequency of the PAL color subcarrier) will be the standard example. A peak deviation of 2.2 MHz, giving a modulation index of 0.5, will be assumed.

The spectrum of this wave is shown in Fig. 68a. The power in the carrier, with modulation, is less than in the unmodulated case, as the total power in the carrier plus its sidebands is constant, as it is for all frequency modulation systems. Using the unmodulated carrier as reference level, the modulated carrier is at -0.6 dB, the first sidebands at 3.6 and 12.4 MHz are at -12 dB, and the second sidebands at -0.8 and 16.8 MHz are at -30 dB.

Negative Frequencies and Unavoidable Distortion It is the meaning and effects of these sidebands on *negative frequencies* that distinguish VTR FM systems. In contrast, consider a *wideband* FM system in which the carrier frequency at 70 MHz is modulated by the same 4.4 MHz signal with the same 2.2 MHz deviation Fig. 68(b). The sixteenth lower sideband, the first to appear on a negative frequency, is at an approximate level of -460 dB and may safely be neglected!

If the signal corresponding to Fig. 68a is fed to a spectrum analyzer or to a sharply tuned filter on 0.8 MHz, a real component will be found, as shown in 68(c); the 0.8 MHz *folded sideband* is spaced 7.2 MHz below the carrier. A demodulator will produce an unwanted output at this frequency that is not harmonically related to the wanted 4.4 MHz.

One source of unavoidable distortion comes from the folded sidebands. The vector diagram corresponding to Fig. 68c is shown in Fig. 69. The wanted output comes from the sum of the two first sidebands, each of amplitude 0.25. The peak deviation is therefore 0.5 radians, or (0.5 X 4.4) = 2.2 MHz. The folded sideband (Fig. 68c) has an amplitude of 0.03 (it has no corresponding upper sideband) and so produces a peak deviation of 0.03 radians or (0.03 X 7.2) = 0.22 MHz. The unwanted output from a frequency demodulator will be down in the ratio of 2.2/0.22,

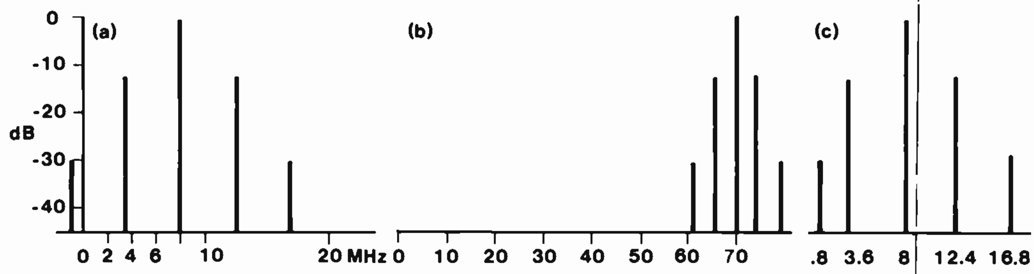


Fig. 68 **FM Signal Spectra**

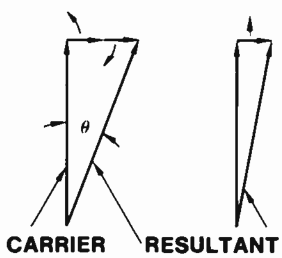


Fig. 69 FM Vectors

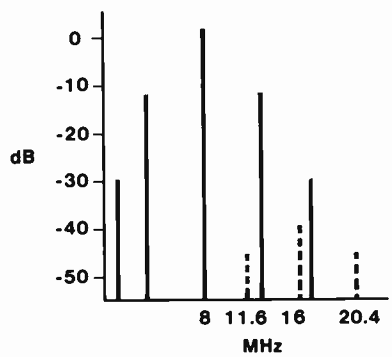


Fig. 70 FM Spectrum - 1% Second Harmonic Distortion

Since the FM system will be subjected both to FM and AM noise (for example, from head-to-tape spacing), all FM demodulators include limiters to eliminate the AM components . Limiters in general introduce odd carrier harmonics [4] and these introduce further amounts of unavoidable distortion, on the same frequencies as those from folded sidebands but generally at higher levels.

Unavoidable distortion can only be kept at an acceptable level by the choice of three parameters: the highest modulation frequency, the modulation index, and the carrier frequency. At a high carrier frequency, the folded sidebands are negligible; as the carrier frequency is decreased, lower order sidebands are folded, and the resulting spurious outputs also decrease in frequency until they enter the wanted passband.

Avoidable Distortion The predominant source of avoidable distortion comes from even order carrier harmonics.

Consider a carrier which is slowly changing once per second between 8 and 9 MHz. Its second harmonic will change once per second between 16 and 18 MHz; the modulation frequency is unchanged but the deviation is doubled.

Suppose the FM signal is fed through an amplifier which introduces 1% of second harmonic distortion. The unmodulated second harmonic carrier on 16 MHz would then have a level of -40 dB; however, the deviation ratio of the second harmonic is twice that of the fundamental, and so is 1.00, with $J_0(\beta)$ equal to 0.77 (-2 dB) and $J_1(\beta)$ equal to 0.44 (-7 dB). The resulting spectrum (Fig. 70) has a 16 MHz carrier at -42 dB, with its first sidebands on 11.6 and 20.4 MHz at -47 dB.

The 11.6 MHz sideband is spaced 3.6 MHz from the 8 MHz carrier, and upon demodulation produces a spurious 3.6 MHz output. (Note that as this is in the wanted passband, it cannot be removed by filtering.) The level of the 11.6 MHz component is (47-12) = 35 dB below each of the wanted first sidebands, or 41 dB below the sum of them; the spurious phase modulation is therefore 41 dB below the wanted, and the output of a frequency demodulator is changed by the ratio of the unwanted to the wanted frequency, or -2 dB. The spurious output is therefore 43 dB down.

Note that a 1% second harmonic has produced approximately a 1% spurious output. The RF circuits of VTRs, both record and playback, must therefore introduce very low levels of second harmonic distortion.

Other possible sources of even-order harmonics are dc in the head windings, dc magnetic fields in the area of head-to-tape contact, and ac fields synchronous with the head scanning rate.

Straight Line Equalization Conventional FM systems generally use bandpass responses in which all significant sidebands are amplified equally. However, it can be shown [5] that any response in which the voltage gain varies linearly with frequency (Fig. 71) does not distort the FM signal; all except the flat response do introduce unwanted amplitude modulation, which can later be removed by a limiter. An intuitive explanation can be seen from the vector diagrams of an FM signal at the time of peak phase shift (Fig. 72a) and zero phase shift (Fig. 72b). In the first case, each pair of upper and lower sidebands is rotated 90° more than the previous pair; in the second, odd pairs cancel and even pairs add. The resultant vector has the same length in each case, as required to give a constant amplitude FM signal.

Suppose this signal is fed through a *straight-line* equalizer (Fig. 72), and that the gain at carrier frequency is unity. Then the increase in gain on each lower sideband is precisely balanced by the decrease on the upper sideband, and the resultant vector in Fig. 72a is unchanged. However, in Fig. 72b the odd order sideband pairs no longer cancel, and the length of the resultant vector increases at one time and decreases 180° later. Thus the amplitude is changed and spurious AM at the modulating frequency has been introduced.

Mathematical analysis shows that the instantaneous carrier frequency must not pass through the point of zero amplitude of the linear response (Fig. 74, point A). This is an obvious practical limitation, since at such times the signal would have zero amplitude. Note that the restriction says nothing about sideband frequencies which always exist on both sides of point A, and may even occur at A without distortion.

The analysis also says that the characteristic passes through zero frequency, as shown dotted. This is not realizable, and may be considered another facet of the folded sideband problem.

In practical systems, the deviation ratio is chosen so that the amplitude of sidebands above frequency A and below zero is small. No response above A is provided, which introduces a small but acceptable level of distortion.

Noise in VTRs Noise in VTRs comes from three sources (Fig. 75):

a) tape noise

b) head noise

c) electronic noise

Tape noise is approximately uniform in flux, and so signal/tape noise is approximately constant with frequency (both being equally affected by spacing and head losses).

Head noise increases with frequency due to increasing core and copper losses. It shows a peak at head resonance which is typically above the wanted band (some early VTRs put it in the band and included electronic compensation to cancel its effects). Electronic noise is approximately flat. The resultant signal/total noise therefore decreases rapidly with frequency. Since in the recorded signal each lower sideband always has an upper sideband of equal amplitude, a playback equalizer that emphasizes the lower at the expense of the upper will give a better SNR. A straight line equalizer in which point A (Fig. 74) is moved to the lowest possible frequency gives the highest SNR. Frequency A is generally chosen just above the frequency of the highest first sideband; it typically gives an improvement of 10 dB over a flat system while introducing less than 1% distortion.

5.3 RECORD ELECTRONICS (McSweeney)

Modulator Figure 76 is a block diagram of a typical single head record system, as found in a type C format VTR. The source video is terminated at the input to a variable gain amplifier. Gain adjustment provides the correct blanking-to-peak-white deviation. The input video is ac coupled and a feedback clamp is used to stabilize the back porch dc level. The clamp has a fast

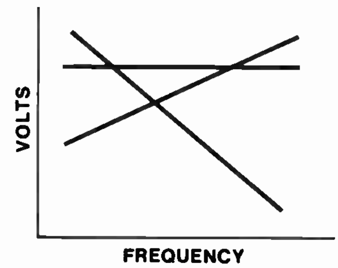


Fig. 71 Straight Line Equalizers

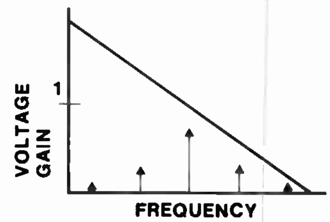


Fig. 73 Spectrum with Straight Line Equalizer

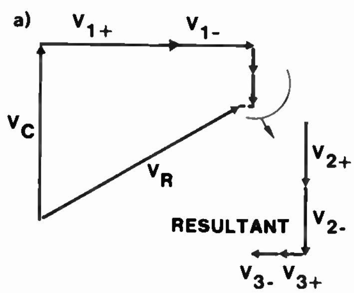


Fig. 72a Peak Phase Shift Instant

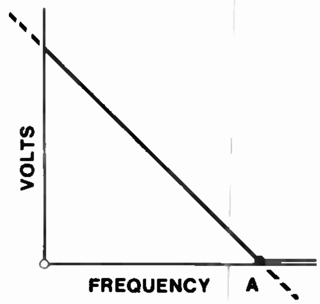
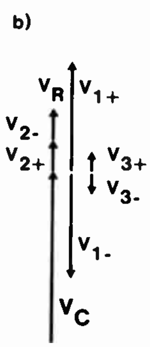


Fig. 74 Straight Line Equalizer Limitations



V_C = CARRIER

V_1 + UPPER & LOWER
V_1 - FIRST ORDER SIDEBAND PAIR

V_2 + UPPER & LOWER
V_2 - SECOND ORDER SIDEBAND PAIR

V_3 + UPPER & LOWER
V_3 - THIRD ORDER SIDEBAND PAIR

V_R = RESULTANT

Fig. 72b Zero Phase Shift Instant

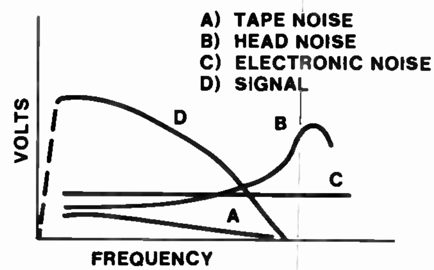


Fig. 72 Vector Diagrams on FM Signal

Fig. 75 Sources of Noise

time constant of about 10 television lines, to minimize the effects of hum on the input signal. Pre-emphasis is then applied as demanded by the standard on which the equipment is operating. A low-pass filter to eliminate out-of-band frequencies, and a peak white clip circuit before the modulator, can be used to protect against over-deviation. As the FM modulator needs to deviate a high percentage of its center frequency, i.e., $\frac{2.2}{8}$=27.5% in the example given in Section 4.2, a multivibrator oscillator is generally chosen. The important design criteria are linearity and minimum even-order harmonics. Linearity is an inverse function of the dead time of the oscillator, and can be minimized by fast switching and minimum recharge times. However, some compensation for nonlinear effects is often required. An oscillator operating at twice the desired frequency, followed by an appropriate divider, can be used to achieve excellent symmetry.

In an alternative beat-frequency approach, two high frequency reactance oscillators, offset from each other by the blanking level frequency, e.g. 108 MHz and 100 MHz, are deviated in opposite directions. Linearity is good in this case as the deviation is a low percentage of the center frequency, and cancellation of square-law non-linearities takes place. The resultant modulated signal differs from the multivibrator output in that it is sinusoidal in nature.

Automatic Frequency Control The modulator back porch frequency can be stabilized by an automatic frequency control loop, as shown in Fig. 76. This frequency is compared to a standard, such as a crystal oscillator, and suitable correction applied.

Record Amplifier The modulated signal is applied to the record head thorough a record amplifier. This provides a current drive with amplitude adjustable to give the maximum RF playback level during the set-up procedure. Adjustment is made to just saturate the tape at carrier frequency. Above this saturation level, short wavelength demagnetization will occur. The amplifier can be a *current switching* type for the square wave signal, but must be linear for the *sine wave* method to avoid generating harmonics. The resulting frequency spectrum on tape is the same for both techniques, as the tape acts as a limiter to the sine wave, introducing odd harmonics just as in the case of the current switching method. Levels of even-order harmonics must be kept below -40 dB, to keep *moiré patterns*, i.e., the avoidable distortion products discussed in Section 3.2, to acceptable levels in playback.

Record equalization is employed to produce either a constant current over the frequency spectrum for Alfesil heads, or a desired roll off with increasing frequency for ferrite heads.

Record current optimization involves a combination of record and playback which must be at slow tape speed unless the recorder has simultaneous playback. Playback RF is monitored for peak output as the current drive is varied.

The output of the record amplifier is normally routed to the rotating head in a balanced manner through a rotary transformer in the scanner assembly.

Color Field Identification Information derived from the record video signal is used for the recorded control track. Vertical sync and an identification pulse for the first field in the sequence of four in NTSC (eight in the PAL system) are required. In playback, the machine is *color frame synchronized* by locking color field number one of the control track to color field number one of reference video.

When input signals meet the RS170A specification (or the EBU equivalent) for subcarrier-to-horizontal-sync (Sc-H) phase, detection can be consistent. Arbitrary decisions are necessary if this phase relationship is close to 90° of a subcarrier cycle away from the center value of the specification. A fixed amount of hysteresis, for example ± 45°, applied after the initial decision-making process, can prevent frame jumping of the I.D. pulse due to (Sc-H) phase drift or detector ambiguity in this region.

In playback, the color field information should be ignored after initial capstan servo lock.

A calibrated detection system can indicate the (Sc-H) phase relationship of input video by metering or other monitoring, such as the LED (light emitting diode) shown in Fig. 76.

5.4 REPRODUCE ELECTRONICS A block diagram for a single-head playback system is shown in Fig. 77.

Pre-Amplifiers Figure 78 shows gain versus frequency response for different values of pre-amplifier input impedance. The high-input impedance approach has the disadvantage that resonance cancellation is required. This involves frequency and Q adjustments which must be altered as the head wears or is replaced. A negative-feedback, low input impedance pre-amplifier overcomes this problem with a small sacrifice in noise figure, fixed compensation for the -6dB per octave response is easily applied later.

The mid-impedance approach is achieved with partial negative feedback, and requires no resonance compensation if head parameters do not vary widely. Use of a step-up transformer lowers the *knee frequency* of the feedback configurations, i.e., the frequency at which $Zh \approx R_{in} \cdot \frac{T1^2}{T2^2}$. *The turns ratio is optimized for best SNR across the spectrum.*

Signal-to-noise requirements dictate the choice of input stage devices used. Field effect transistors can have an advantage over bipolar in H.F. matching of the complex source impedance of the head. In most systems, however, tape noise is dominant and a bipolar differential amplifier, for example, can give adequate S/N while excelling when isolation requirements are stringent, as in simultaneous record/playback modes.

Equalization To correct the wavelength and frequency dependent losses in the record/playback process, a network with constant group delay and high frequency amplitude boost is ideal. This boost restores to flat the frequency response of the carrier and its important sidebands, and is made variable to allow correction of variations in heads and tape. An aperture corrector (cosine equalizer) has the required characteristics. In the implementation shown in Fig. 79a), the signal 79b) at the source-terminated delay line is combined in an adjustable amount with the flat output signal from the delay line. Amplitude compensation within the range shown in 79c) for the head-tape frequency response is made by the adjustment of K. This avoids differential gain and frequency response problems, which occur when the output of the equalizer is not flat for the deviated carrier and its sidebands.

Ferrite heads have less response curvature at low frequencies than Alfesil. Matching can be achieved with use of a second delay line connected as shown in Fig. 80a. Here, the low frequency curvature is controlled by the amplitude of K_1, and the amount of H.F. boost by K_2. A differential gain adjustment is also often provided. This operates on the carrier, altering its amplitude response with respect to its sidebands as it deviates from black frequency to white. Finally, to improve the S/N of the demodulated signal, a straight line equalization network as described in 3.2 precedes the limiter stages. This should have constant group delay while attenuating the higher frequencies.

Drop-Out Detection As shown in Fig. 77, an Automatic Gain Control (AGC) circuit stabilizes the RF amplitude prior to drop-out detection. The detector is designed to sense a drop in signal amplitude greater than 16 dB, and lasting slightly longer than the period of the lowest carrier frequency. Some amount of hysteresis, perhaps 4 dB, is then applied to this threshold level to avoid a marginal decision point. The drop-out pulse generated in this fashion is used to clamp the output video to blanking level, and to gate in compensation in the time base corrector, (see Drop-Out Compensation Section 6.4).

Demodulation Sufficient limiting is required to remove amplitude modulation. This enables demodulation of varying signal levels down to the theoretical S/N threshold point. Balance adjustments are included in the limiter strip to minimize even-order har-

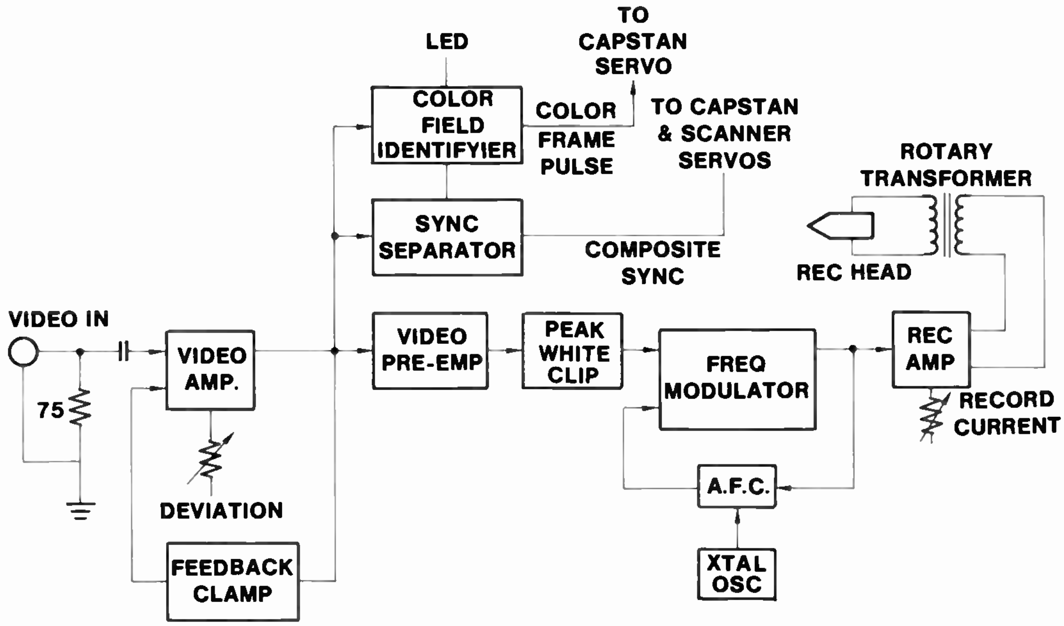


Fig. 76 Single Head Record System

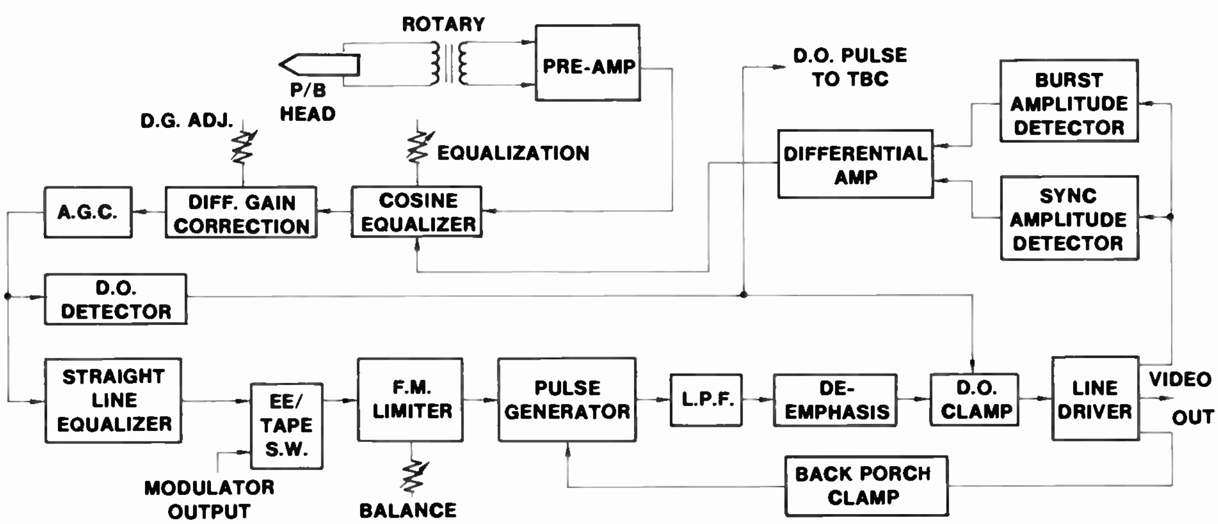


Figure 77 Single Head Playback System

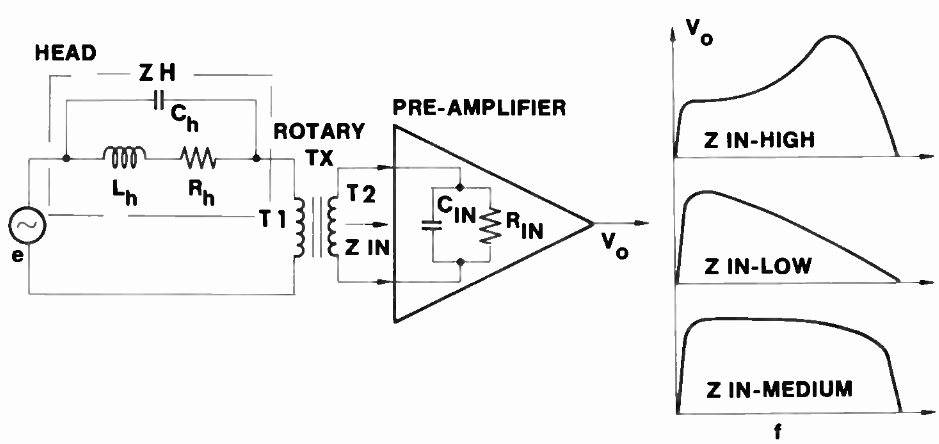


Fig. 78 Response as Function of Pre-Amp Input Impedance

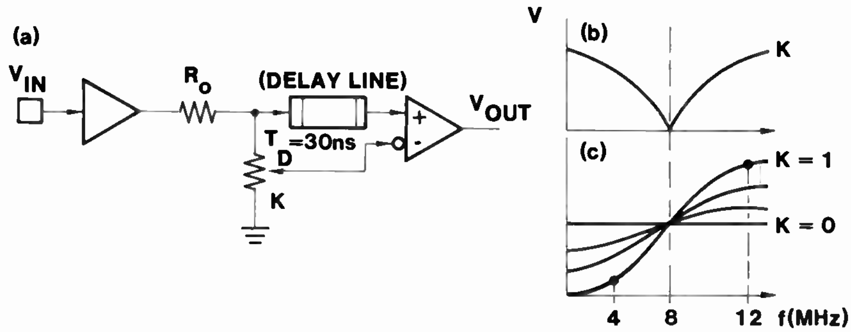


Fig. 79 Aperture Correction by Cosine Equalizer - Single Delay Line Method
a) Circuit b) Response at Input to Delay Line c) Range of Compensation

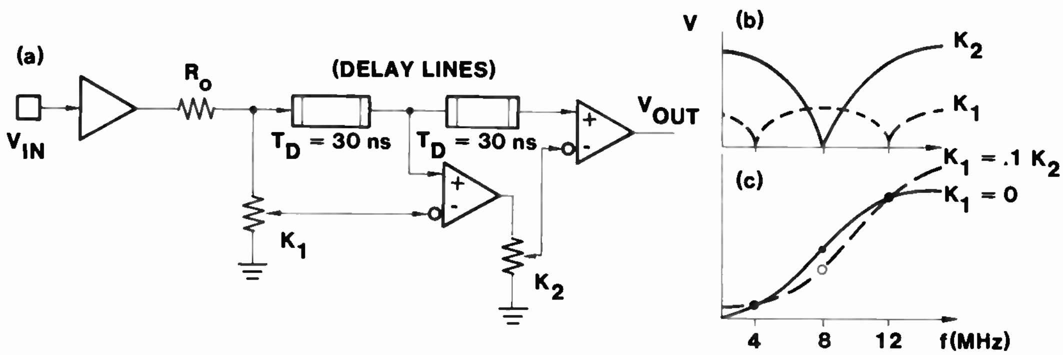


Fig. 80 Aperture Correction by Cosine Equalizer - Two Delay Line Method
a) Circuit b) Response at Inputs to Delay Lines c) Range of Compensation

monics. A pulse-counter type discriminator is the most suitable method for achieving good linearity over the wide carrier deviations involved. Here, a pulse is formed at each cross-over of the limited RF, and integrated by a low pass filter. Filtering requirements are made easier as this doubles the fundamental carrier frequencies, which are then rejected by a low pass filter with high stop-band attenuation. Any group delay difference across the video pass band is corrected by appropriate phase equalizing networks.

The filter is followed by an amplifier which applies video de-emphasis and correction of any pass-band losses. Drop-out clamping is followed by a video line driver providing video to a feedback back-porch clamp, *autochroma* circuitry, and the machine output.

Autochroma By amplitude detecting the sync and burst of the output video and comparing their levels, a difference voltage is generated. This is used to control the response of the cosine equalizer, making the burst level equal to the sync level. When monochrome status is detected, this control is switched to the manual mode. In segmented formats, response changes as the head scans its tracks are more noticeable than on one-field- per-track systems. Line-by-line detection is needed to correct the chroma amplitude across the scan in combination with head-by-head correction for longer term errors.

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6. TIME-BASE CORRECTION

E. Stanley Busby, David E. Trytko, Steven Wagner

6.1 History of Time-Base Correction (Busby)

Electromechanical In very early quadruplex VTRs, the headwheel rotated at a multiple of the power-line frequency. The timing of vertical sync was unrelated to that of other video sources in the studio. A video switch between a VTR and another source caused a vertical scanning resynchronization in receivers, seen as a disturbing picture roll.

The first level of synchronization of VTRs with the studio's synchronizing generator was accomplished through the use of two servomechanisms:

1. A capstan servo, which positioned a recorded track containing a vertical sync pulse under the headwheel at reference vertical time.
2. A headwheel servo which adjusted the phase of the headwheel rotation until playback and reference vertical pulses were coincident.

Both of these servos are discussed in greater detail in Section 7.

The departure from ideal synchronism was on the order of a few microseconds. Only slowly changing perturbations were corrected, however, due to the low sampling rate of 50 or 60 Hz.

Mispositioning of the tape guide, which forces the tape against the headwheel, was responsible for a particularly objectionable time disturbance called *skewing,* illustrated in Fig. 100. A tape guide servo was devised which compared the interval between the last horizontal sync pulse in a head pass and the first one of the next pass, and compared it with the average interval, supplied by a phase-locked oscillator. The error operated a small motor which positioned the tape guide for minimum error.

The remaining time base error had three principal spectra:

1. Slowly changing components caused mainly by variation in tape friction.
2. Components at the head-pass rate, stemming from non-ideal and not-easily-corrected deviations in the values of parameters of the headwheel and tape guide geometry.
3. Very rapidly changing components caused by imperfect ball bearings in the head wheel motor.

The horizontal scanning generators in receivers of the day were phase-locked oscillators to improve noise immunity. They could follow a slowly changing phase, but not a rapidly varied one.

Early Color Correction The stability required of the color subcarrier is orders of magnitude greater than an electromechanical servo can deliver. The first color playback from quadruplex machines stabilized the chrominance component only, leaving the luminance uncorrected.

In one implementation the chroma was filtered from the composite playback signal, and an oscillator was phase-locked to each color burst. This oscillator was used to demodulate the chroma to color difference signals, which were then re-modulated using a stable subcarrier and mixed with the uncorrected luminance, as shown in Fig. 81.

In another implementation, an oscillator derived from playback burst was used to translate the chroma component to a higher frequency well out-of-band, where it was filtered and returned to the spectrum by heterodyning with a stable frequency derived from reference color burst.

Both these systems were called *heterodyne color,* and produced viewable images. The relationship between horizontal scanning and the subcarrier frequency was not maintained, and artifacts of this deficiency could be seen at vertical edges of colored objects.

Full Monochrome Synchronization An improvement was made to the mechanical servomechanism which further reduced time base error, discussed in more detail in Section 8.

Once vertical synchronism was attained, the system changed modes to compare playback and reference horizontal pulses. The wider bandwidth resulting from the higher sampling rate reduced residual low-rate time base error to less than one μsec.

With full synchronization, it was possible for the first time to mix a VTR playback signal with other video sources, without an interruption in synchronizing signal timing.

Electronic Time Base Correction Shortly after this time, a voltage-variable video delay line was developed to treat short-term errors. It had two principal modes:

1. For VTRs not equipped with the new servo mentioned above, playback horizontal sync pulses were compared with a phase-locked oscillator having a time constant similar to that used in receivers. The error signal was used to adjust the delay line over its 2.5 μsec to 3.5 μsec range.
2. For systems with the new servo, playback horizontal pulses were directly compared to reference horizontal. A low bandwidth feedback path was provided to the servo system which caused it to adjust the average arrival time of horizontal sync such that the electronic corrector operated in the center of its delay range.

In this mode, all residual time-base errors were reduced to less than 30 nsec. This was adequate for monochrome, but not for color.

Full Color Correction Yet another electronic corrector was added to the signal processing path, comparing playback and reference color bursts, and manipulating a similar but shorter delay line. The residual error was thereby reduced to about 4 ns., limited primarily by the signal-to-noise ratio of playback burst.

Correction of First-Order (Velocity) Errors Since color burst and sync pulses are available only at horizontal intervals, time base errors are detectable only then, and represent the accumulated error during one scan line. In the presence of a changing time error, color was correct at the outset of a horizontal scan, but became progressively worse as the line proceeded, reaching a maximum at the right edge of the picture. For the most part, these errors were a function of the headwheel and tape guide geometry, and repeated at the head pass rate. The error magnitude was proportional to the rate of change of time-base error.

A first-order corrector was devised which, for each of the horizontal line periods (16 or 17) scanned during a head pass, measured and integrated the error steps at each horizontal boundary to improve noise immunity. These stored voltages were used to generate a linear ramp function which was furnished to the color corrector to effect a progressive correction throughout the line.

The residual error, in the end, was either random, or greater than first-order. The processing sequence of an entire analog system is shown in Figure 82.

A Hybrid System As either a forerunner or outgrowth of digital time-base correctors, a system was developed in which the playback video was sampled at an adequately high rate, but not quantized. The analog samples entered a charge-coupled analog delay line, and passed through it at the sample rate. The delay through the line was inversely proportional to the clocking frequency, which was varied to make the output uniform with time.

The dynamic range of the charge-coupled device was limited, and the approach was applied in systems, which for other reasons, had a low signal-to-noise ratio.

6.2 Digital Time Base correctors (Busby)

The decrease in cost of digital circuits, especially memory devices, made digital time-base correctors an attractive alternative to analog systems. This was especially so for correctors used with helical scan VTRs, whose time error accumulated for an

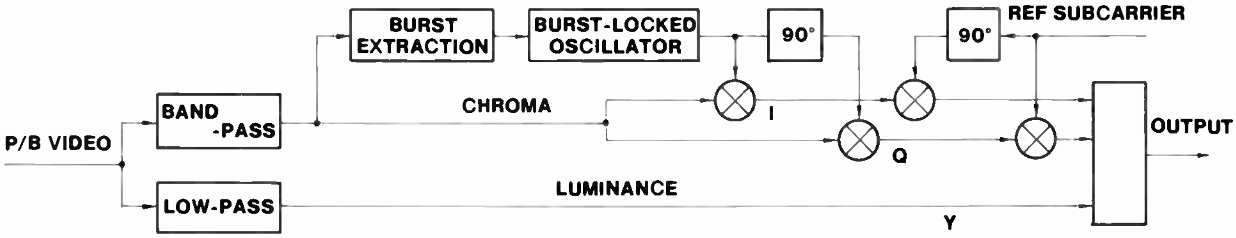


Fig. 81 Signal in Early Color Corrector

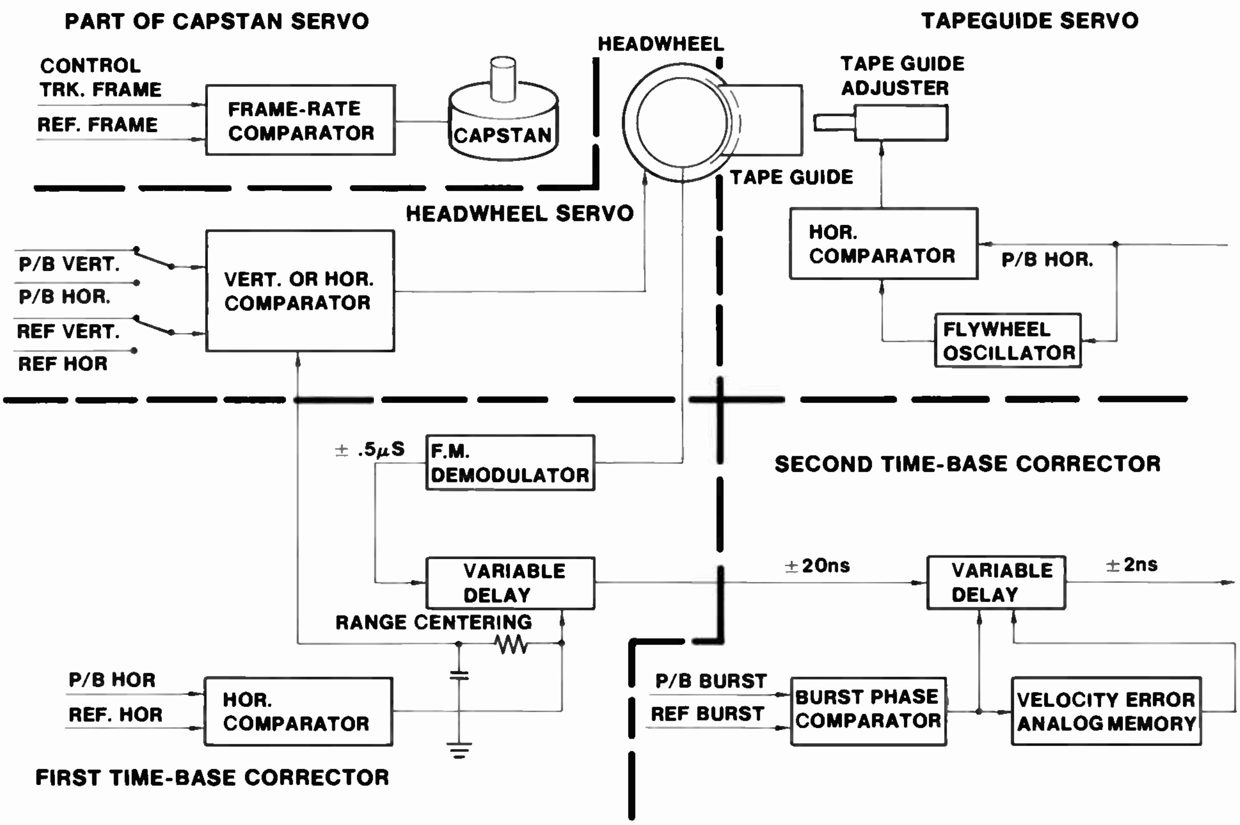


Fig. 82 Processing of Complete Analog system

entire field, and which therefore required a correction range of tens of microseconds. Large-range analog systems required long, expensive, analog delay. Long digital delay involved only additional memory.

As in any digital video system, the input signal must be dc restored, bandwidth limited, sampled and quantized. In early digital TBCs, analog to digital conversion was accomplished with discrete circuits, using two sequential four-bit measurements. This method was soon replaced by an integrated circuit one-look flash converter, used in modern units.

A digital time base corrector is characterized by sampling and writing into memory at a frequency f_1, while recovering and outputting samples at another frequency f_2. Of f_1 and f_2, one is derived from the time-unstable playback, and the other from a stable reference. The average frequency of f_1 equals f_2. The sampling frequency is typically a multiple of the color subcarrier, usually the third or fourth.

If the unstable frequency is derived from playback burst by setting its phase at each burst time, the system is a line-by-line corrector. Instantaneous discontinuities in timing, as might be produced in quadruplex VTRs at head-switch time, or as the result of an edit, will be corrected by such a system, but velocity errors will not.

If the unstable frequency is derived from the playback signal using a phase-locked oscillator with a fairly long time constant, instantaneous discontinuities are uncorrected, but some reduction of velocity error takes place. This method is frequently used with helical scan recorders which are relatively free of sharp time discontinuities in the active part of the picture. It also has the advantage of being more immune to noise and occasional missing pulses.

In professional systems, the stable frequency is always derived from the studio's synchronizing generator, so that the output video may be mixed with other video sources. In lower cost systems, the stable frequency may be derived from the playback signal, using a phase-locked oscillator with a long time constant. Professional TBCs often offer this mode as a switchable option, for use in processing the playback of VTRs which have no servo system.

Otherwise, the playback timing of the VTR is adjusted so that the average delay through the TBC is half the total available, maximizing the correction range. Delay lengths range from one horizontal line time to several lines. Helical scan VTRs which offer slow, fast, and reverse motion accumulate large time errors, and the longer the delay in the TBC, the wider is the range of speeds over which the VTR can perform these special effects. Details of the interaction between variable speed playback and the TBC appear in a later section of this chapter.

Figure 83 illustrates the major components of a digital TBC. A phase-locked oscillator operating at three or four times Fsc is locked to playback video using a fairly long time constant. At the arrival of each color sync burst, its output is phase adjusted such that when divided by three or four, the result is synchronous with playback burst. This phase is maintained throughout the horizontal scan.

The band-limited playback video is sampled and converted to an eight-bit unsigned binary quantity. It is typical to temporarily store three or four samples in high speed memory to form a 24 or 32 bit word which is then strobed into the main memory once each cycle at Fsc, to extend the read/write time.

The choice of the number of samples stored temporarily is a function of the main memory bandwidth, and is independent of the sampling frequency. The multiplexing into the main memory, must, however, match the de-multiplexing at its output.

The output clock is the same multiple of a stable subcarrier. Its output, suitably divided, is used to recall words from the main memory. The word is then commutated at the sampling rate to obtain the original stream of samples which then are applied to a digital-to-analog converter. The D/A is followed by a resampler to remove transients, and by a low pass filter to remove any out-of-band energy. The response of the output filter is sometimes shaped to compensate for the $\frac{\sin(f)}{f}$ loss associated with the sampling process.

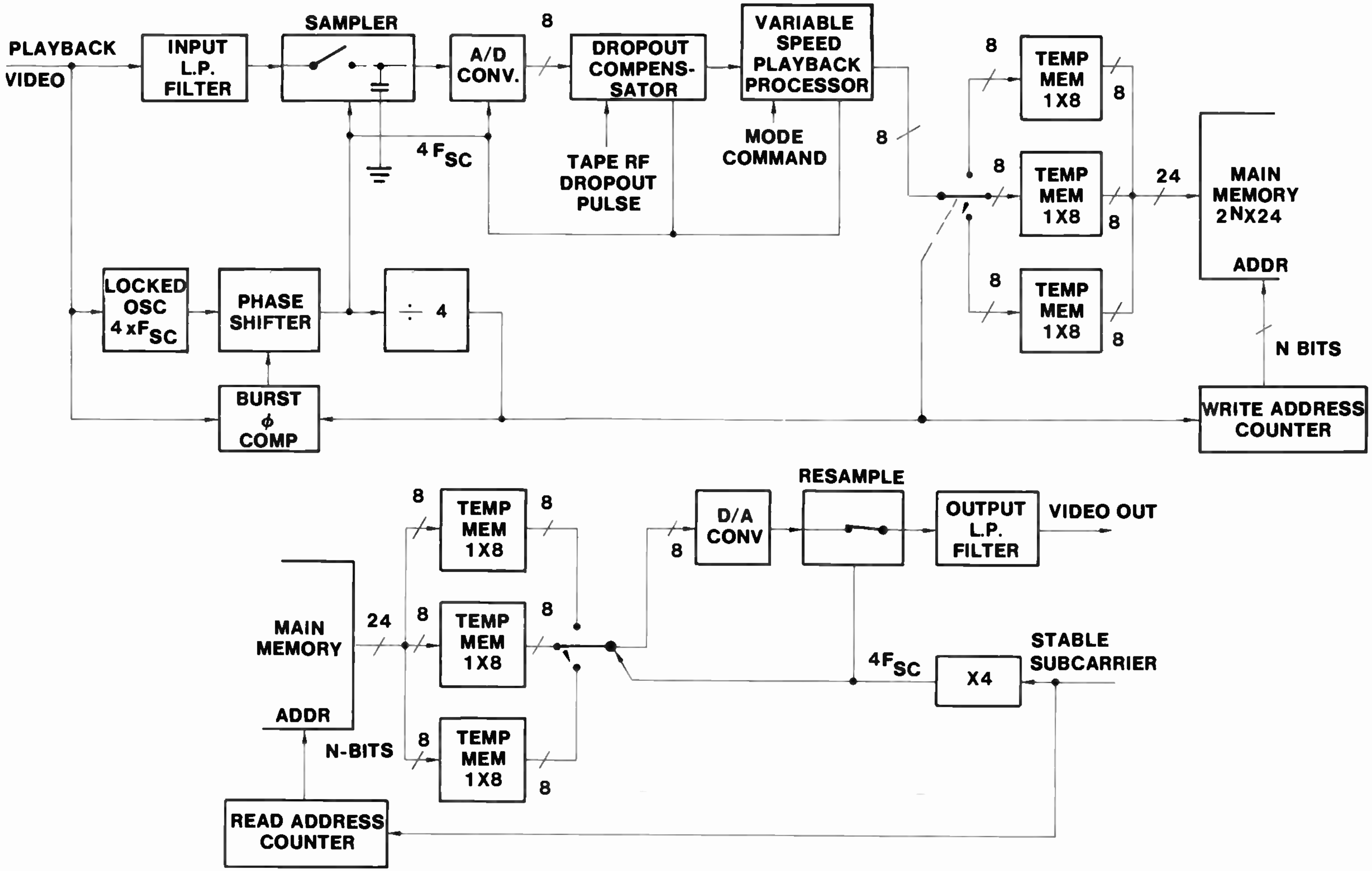


Fig. 83 Major Components of a Digital TBC

6.3 VELOCITY ERROR COMPENSATION (Trytko) Off-tape video signals contain many instabilities that must be eliminated to reproduce a high quality color picture. While the line-by-line correction provides a significant improvement in the overall signal stability, it nonetheless fails to completely eliminate all timebase errors. Those that remain, caused by geometric errors, tension variations, or atmospheric conditions, are termed *velocity errors.* They are the result of the difference in the effective head-to-tape speed between record and playback, and are characterized by a progressive chroma phase shift throughout each horizontal line. Therefore, although the line-by-line correction eliminates the errors that exist at the beginning of each horizontal line, the velocity errors generated throughout the line remain.

The constant change in magnitude of line-by-line error measurements indicates that the overall timebase error profile is more complicated than a simple zero-order approximation (See Fig. 84). A zero-order estimation is the profile provided by the line-by-line process. The visual result of using this approximation alone is a video signal whose instabilities (and therefore chroma impurities) increase throughout the duration of the horizontal line. Clearly, a more accurate error approximation is required for high quality video reproduction.

As seen from Fig. 85, the zero-order approximation provided by the line-by-line process can be significantly improved through linear interpolation. That is, a first-order approximation can be constructed by assuming that the rate of change (slope) throughout the line is constant. Considering Section AB in Fig. 85, a linear interpolation is performed to distribute the step changes in the line-by-line error samples across the horizontal line. Note that the slope "M" is constant and requires advance knowledge of the line-by-line error of line 3 at the beginning of line 2. This condition implies a non-causal process which can be performed with some type of video delay of at least one horizontal line.

More radical errors, such as impact errors, require an even more detailed error profile before they can be substantially eliminated. These types of errors are primarily the result of tape deformation caused by the impact of the rotating video heads as they make initial contact with the tape. This kind of disturbance creates a condition where the rate of change of error throughout the line can no longer be considered constant. Thus, the presence of *acceleration error* becomes apparent and may well require at least a second-order profile to be substantially reduced.

Manufacturers use various methods of eliminating these higher order velocity errors. In general, however, the basic method of correction incorporates a sampled system of line-by-line error measurements that are in some way interpolated into a more accurate and detailed error profile.

6.4 DROP-OUT COMPENSATION (Wagner) In developing new videotape and videotape recorders, much effort has been made to reduce the frequency and severity of tape dropouts. Nevertheless there is still some dropout activity in practical videotape recording systems. Additionally, dropouts increase rapidly as tape becomes worn and contaminated with dust and other matter.

To minimize the visibility of residual dropouts the technique of dropout compensation must be used. Dropout compensation is a method in which those portions of a playback video signal containing dropouts are first detected, then replaced with a video signal which is dropout-free. The dropout-free replacement video should be a good estimate of the missing video for the masking process to be effective.

Dropout Characteristics Dropouts in videotape recording have statistical characteristics which greatly affect dropout compensator design. When they occur, dropouts are almost always much shorter than one scan line in duration, and the time between dropouts is usually many scan lines, even in areas of severe dropout activity. Typically, dropouts might occur once every few seconds and last for a small fraction of a scan line.

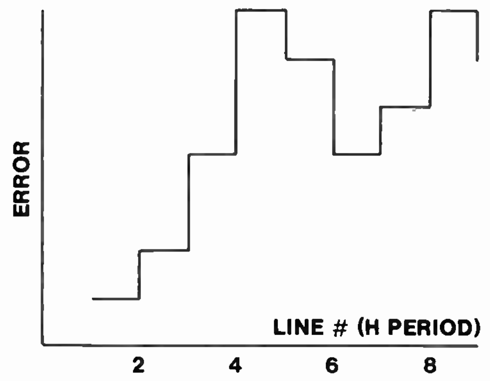


Fig. 84 Line-by-Line Error Profile (Zero Order)

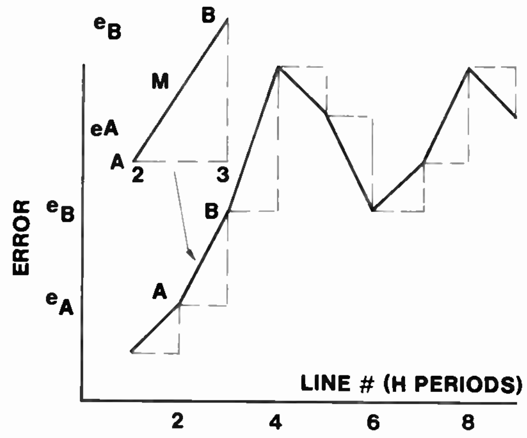


Fig. 85 First Order Interpolation of Velocity Error

Basic Previous-Line Dropout Compensator Method Effective dropout compensation relies on a good choice of substitute video when playback dropouts occur. It was realized in the early 60's that the video content of adjacent scan lines of a field are usually similar (ignoring for the moment the fact that subcarrier phase will not be identical). When a dropout occurs in a given line, then a section of the previous line can be substituted for the section of the line affected by the dropout (Fig. 86). Since the two lines will tend to be similar, the substitution is nearly invisible. This method is known as *previous line dropout compensation.* It is the most common form of dropout compensation in use today and will now be discussed in detail.

Fig. 87 shows the block diagram of a simple monochrome dropout compensator. The key element here is a one horizontal line delay that has off-tape video as its input. The output of the delay is thus video from the previous input scan line. When the input video contains a dropout the switch is moved from the *normal* to the *dropout* position and input video is replaced with dropout-free video from the previous line.

Occasionally dropouts occur that are one or more scan lines in length. The simple DOC described here uses recirculation to handle this case. Notice that when the switch is in the *dropout* position, the delay line also receives one-line-previous video at its input. This prevents any dropouts from ever entering the delay line so that its output will always be dropout-free. The delay line will always contain the most recent video that contains no dropouts even if it is from many lines previous.

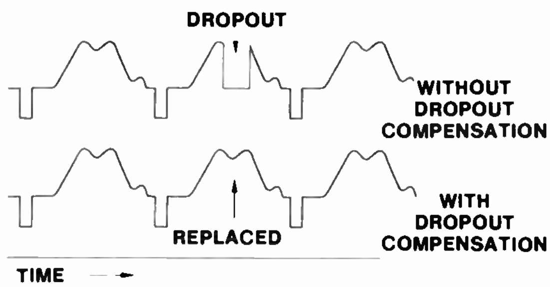


Fig. 86 Waveform Showing Without D.O.C. and with D.O.C.

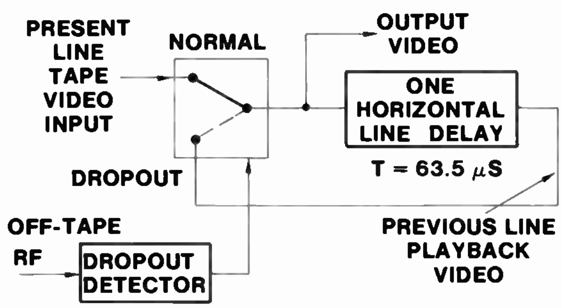


Fig. 87 Simple Monochrome Previous-Line D.O.C.

Full Color Dropout Compensation All DOC's rely on nearby lines for replacement video in the case of a dropout. This replacement is straight-forward for monochrome but is more complicated for color television systems because the color encoding structure is not identical for each horizontal line. Direct substitution video from an adjacent line has chrominance that is incorrectly encoded for the incoming line, and would result in grossly wrong color if used in place of a dropout. There are several solutions to this problem. The simplest is to take substitute video from a recent scan line that has the same color encoding structure as the line containing the dropout.

In the NTSC standard, every other scan line has the same chroma encode subcarrier phase. Thus if video contains a dropout, substitute video from two lines previous can be used directly in place of the dropout and will give correct color. The main disadvantage is that the substitute video is spatially further away from the dropout and as a consequence will be statistically less similar to the missing video. This method has been used commercially in the past, and is judged to be marginally acceptable, compared to newer methods. In the PAL system the color encoding structure repeats after four lines, hence substitutional video must be taken from four lines away to have the same chroma structure as the video containing the dropout, and this is much too distant spatially for adequate performance.

A more satisfactory approach is to use previous-line video for substitution and to modify or process it to make the color encoding structure the same as the line containing the the dropout. This technique is used in NTSC for the D.O.C. shown in Fig. 88. As in the monochrome D.O.C of Fig. 87, tape playback video first passes into the one line delay. Previous-line video at the output of the line delay is then separated into luminance and chrominance channels by luminance lowpass and chrominance bandpass filters, respectively. In NTSC, chrominance on a given line has chroma subcarrier opposite in phase from that of an adjacent line of the same field. Thus the output of the Chroma bandpass filter is inverted to yield the same encode subcarrier phase as the incoming off-tape video. Since only the color encoding structure changes from line to line, the luminance from the previous line is substituted directly.

The PAL-I system is somewhat more complicated in that the color subcarrier of the adjacent line is shifted in phase by 90°, and the V color difference signal is opposite in polarity. One common method of PAL-I dropout compensation is shown in the D.O.C of Fig. 89. As in NTSC, the previous-line video at the delay line output is first separated into luminance and chrominance by lowpass/bandpass filtering. The chroma signal at the bandpass filter output is further decoded into color difference signals U and V using a decode subcarrier that matches that of the previous-line video. U and V, being independent of the color structure, can be re-encoded into chroma of any subcarrier phase. Here, the encode subcarrier phase is the same as that of the off-tape video, giving previous-line chroma identical in structure to that of the off-tape video. Adding previous-line luminance to the re-encoded chroma gives a composite color video signal derived from the previous line that can be substituted directly for dropouts in the off-tape video, and will give proper color.

Further Improved DOC Methods The full color DOC's just described have one weak point. Since the composite video must be separated by lowpass and bandpass filters, there will necessarily be some loss in signal fidelity when a dropout occurs. In particular, the luminance bandwidth will be reduced, and high frequency luminance will be separated as chrominance by the bandpass filter, and will be processed incorrectly. Both of these defects can be noticeable for picture material of high luminance detail, especially if the lowpass and bandpass filters must be simple low-order designs for cost or space reasons.

A technique presently in wide use has an additional one line delay to effectively form a comb filter-based luminance/chrominance separator. A comb filter is a device which can be used to average video from adjacent lines in such a way that luminance is passed through with full bandwidth, if the picture content is similar from line to line. A comb filter-based DOC for the NTSC system is shown in Fig. 90. As with DOCs already discussed, the off-tape video passes first into a one-horizontal line delay. The one-line delayed video from the previous scan line is then separated into luminance and chrominance using conventional lowpass and bandpass filters. Luminance is passed straight to the output with no further processing, while the separated chroma is passed through an additional one line delay. The *dropout* video thus consists of luminance from the previous line and chroma from two lines earlier. Since the chroma structure in NTSC is the same every two lines, this two-line-previous chroma has the same chroma phase as incoming video and will give correct color when used in substitution.

How is this system better than previous ones? Consider again the DOC of Fig. 90. Low frequency luminance passes through the lowpass filter, and high frequency luminance near chroma passes through the bandpass filter. If we assume that the luminance is similar from one line to the next, then the luminance signal at the output of delay #2 will be the same as its input, and one line delay#2 can essentially be ignored for the luminance signal. Thus for luminance, the outputs of the lowpass and bandpass filters are added directly together, and if the filters are complementary, the resulting frequency response for luminance will be perfectly flat. This differs from the one-line delay based DOC's that necessarily reduce luminance bandwidth. The property of flat luminance response depends on the luminance being similar from line to line, which is generally the case, and on the lowpass and bandpass filters being approximately complementary. The sharpness of the filters does not affect the flat luminance property, so simple filters may be used with little visible degradation.

One seeming disadvantage of the method is that chroma is derived from video two lines removed from the line containing the dropout and hence will be less similar than previous line video. Fortunately, the eye is much less sensitive to mispositioned chroma than to mispositioned luminance, and the tradeoff here is a good one: flat full-resolution luminance derived from the previous line, and chroma from two lines previous.

DOC Circuit Implementation The type of circuitry, analog or digital, used to implement the chosen DOC system can greatly affect such factors as cost, size, complexity, stability and reliability. While workable analog DOC's can and have been built in the past, recent and new designs are digital. While digital designs can be more costly, complex, and space-consuming than equivalent analog ones, the digital system is inherently stable and predictable and requires no calibration or adjustment. Digital integrated circuits are continuously being developed that cost less, do more, and use less power than their predecessors. The DOC function is a feature of modern time base correctors, which are mainly digital, making it especially convenient to implement the DOC in a digital form.

The DOC as Used in Digital Time Base Correctors As shown in Fig. 83, the DOC circuit follows the analog-to-digital converter, where digital video data is first available in the TBC. The output of the DOC then passes to the main memory, or to other TBC enhancements such as variable speed processing, which is described in the next section.

6.5 VARIABLE SPEED PLAYBACK PROCESSING (Wagner) Modern professional helical scan videotape recorders, besides providing excellent performance in standard playback use, also can be used to vary the tape playback speed from zero to greater than normal speed in the forward direction. In addition, they can be operated in a reverse slow motion mode, always maintaining a disturbance-free broadcast quality signal. This is made possible by both the system of automatic scan tracking, described in Section 8.5, and by a unique processing techniques in the TBC. Automatic scan tracking, by keeping the playback head centered on the recorded track over a wide range of tape speeds, eliminates the severe cross-tracking noise which occurs in an unequipped helical VTR

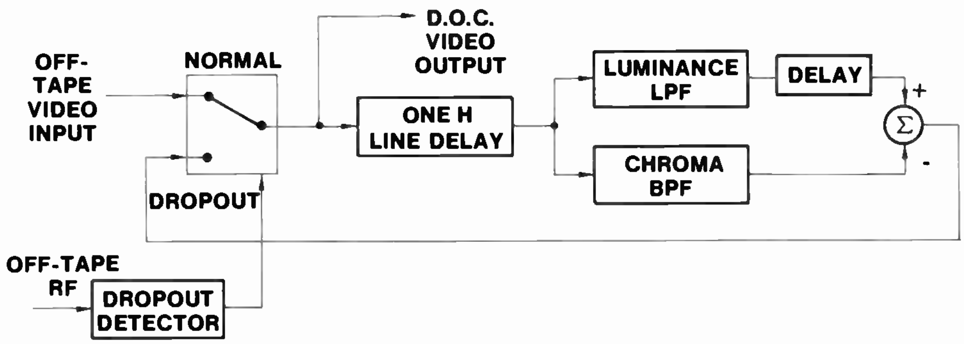


Fig. 88 Color Previous-Line D.O.C (NTSC)

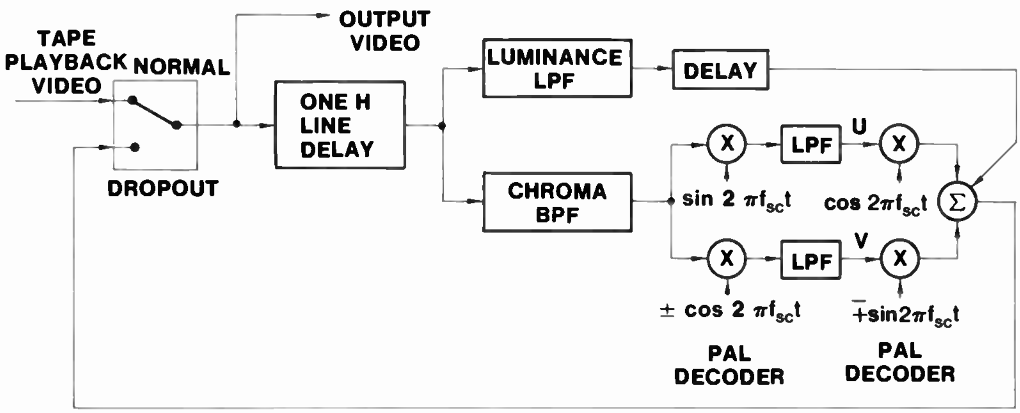


Fig. 89 PAL Color Previous-Line D.O.C.

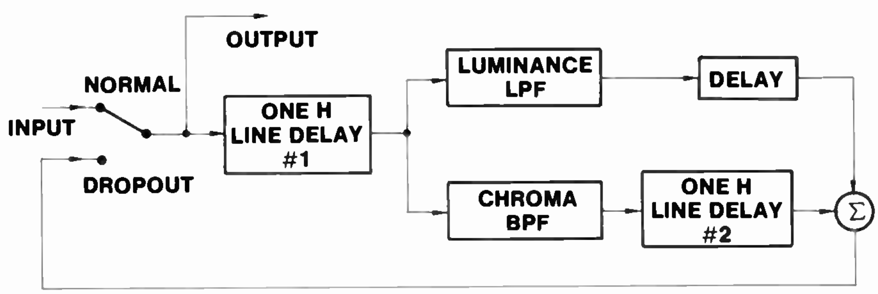


Fig. 90 Comb Filter-Based D.O.C.

at incorrect tape speeds. However, the signal must be processed by the time base corrector to make it suitable for broadcast or re-recording.

Nature of Helical Scan Playback Signal in Variable-Speed Mode The playback signal of a helical scan VTR in the slow motion mode has several properties with which the TBC must cope:

(1) Depending on tape speed, the playback head will skip or repeat a track (one field on a "C" format VTR) on an intermittent basis to stay on the track center. This means that the off-tape video no longer conforms to the color frame sequence determined by the station reference (four fields in NTSC, eight in PAL)

(2) When the playback head jumps a track, there will be a step change in time base error of several lines, occurring in the vertical interval, because of the track geometry on tape.

(3) There will be a constant frequency error in the playback signal of up to about 1%, related to the longitudinal component of the head-to-tape speed.

TBC Operation in Variable-Speed Mode Properties (2) and (3) above can be handled readily by the structure of modern time base correctors. The step time base error is removed simply by shifting the TBC's main memory vertical reset pulse in the amount and direction of the playback video step time base error. The VTR normally sends special control signals to the TBC when the step error occurs, as well as the amount and direction of the error. At first it would seem that property (3) would present a severe problem: if the video contains a constant frequency error then the time base error between the playback signal and the station reference signal is forever increasing, requiring an infinite time window in the TBC. However, the scanner rotation is locked in frequency to the station reference vertical in all modes including variable play, and thus the time base error accumulates only over one field and then resets to zero in the vertical blanking interval. If the frequency error is + 1%, as would be the case in forward 2X normal speed for an NTSC Type "C" helical scan VTR, then the time base error which builds up over a field will be 2% of 262.5 lines, or slightly more than five horizontal lines. This sets a lower bound of six on the number of lines the TBC memory must have to allow variable playback to 2X normal speed.

Variable-Speed Video Processing in TBCs Property (1) above, the skipping or repeating of fields which occurs in the variable speed mode, is the most difficult to handle in the TBC. When and how often this field jumping occurs depends only on playback tape speed relative to normal. As a result, there is no relation between the off-tape field type, and the field type of the station reference. The TBC output field type must match that of the station reference. Therefore in the variable speed mode the TBC must be able to convert or modify any given playback field into any other type field as dictated by the station reference. Conversion without side effects is made difficult by substantial difference in the structure of the fields.

(1) Because of the system of interlace, adjacent fields are offset vertically by one-half scan line.

(2) The color encoding structure is not identical on corresponding lines of different fields.

In NTSC there are two unique color frames, each having two interlaced fields. The fields are normally indicated as fields (1) and (2) of color frame A and fields (3) and (4) of color frame B. Fields (1) and (3) differ in that the encoding chroma subcarrier phase will be 180° offset for a given line on field (1) compared to the corresponding line on field (3). The same is true when fields (2) and (4) are compared. In PAL, the sync to subcarrier relationship and the V axis phase gives four unique frames (eight unique fields). As indicated before, the TBC must convert any off-tape field to the field type dictated by the station reference. The details of this process are discussed in the following sections.

Basic Chroma Processing of the Off-Tape Signal To have correct color playback in the variable speed mode, the TBC contains circuits to process off-tape video such that its chroma structure matches that of the station reference at all times. There are several methods of chroma processing in use that vary in performance and complexity. The most common method uses standard lowpass- bandpass filters to separate luminance and chrominance respectively. Chroma is decoded, then re-encoded as necessary to match the chroma structure required by the TBC reference. A typical system is shown in Fig. 91. The off-tape video passes into a bandpass filter centered at the frequency of the subcarrier with a bandwidth corresponding to that of typical chroma. The off-tape subcarrier and a suitable decoder are used to decode the output of this filter to baseband color difference signals. These are then recoded using station reference subcarrier. In this way the TBC output video always has correct color in variable speed mode independent of playback field type. Since the luminance need not be affected by the chroma processor, the output of the luminance lowpass filter is simply added back to the output.

Improved Chroma Processing Using Comb Filter The lowpass/bandpass chroma processor of the type just discussed has one major drawback: it necessarily band-limits luminance to adequately separate chroma, causing loss in horizontal picture resolution in the processed signal. By adding a chroma comb filter in cascade with the chroma bandpass filter, the horizontal luminance bandwidth of the processed signal can largely be preserved. Fig. 92 shows a comb filter- based chroma processor for NTSC. Off-tape video first enters the comb filter. The comb filter subtracts the composite video of one scan line from that of the adjacent field scan line. The luminance portion of off-tape composite video, if it is similar from line to line, will largely be blocked by the comb filter and instead will take the upper path directly to the output with no resolution loss. This is in contrast to the simpler circuit of Fig. 91, where the composite video must be lowpass filtered to a bandwidth less than subcarrier frequency to adequately separate luminance and chroma.

The output of the comb filter is mainly chroma with some residual luminance which is not line repetitive. The signal is further bandpass filtered at subcarrier to remove most of the residual luminance. Because the comb filter adds full contributions from two lines the chroma will be twice normal amplitude.

When the switch in Fig. 92 is in the *NORMAL* position, the output is simply the unprocessed input with a short delay. This position is used when off tape and reference video fields have chroma which matches on corresponding lines. When the switch is in the *INVERT* position, the inverted, twice amplitude chroma (-2C) at the bandpass filter output is added to the delayed composite signal (Y+C) giving an output of Y-C ; that is, the output has chroma which is opposite in phase from that of the input. The *INVERT* position is used when the chroma phase is opposite on corresponding lines of the off-tape and reference fields. One drawback of the simple comb filter is that it causes some loss of diagonal luminance resolution and a one-scan-line-vertical-offset of luminance and chroma.

Field Interlace Conversion With the chroma corrected by one of the techniques described, the problem of dealing with the interlace structure remains. A broadcastable picture can be obtained with no correction of the interlace at all. The off tape field is used directly as the output field whether or not it is of the same type. The main impairment from this is a vertical bounce of the playback picture of one frame line at a rate depending on playback speed, being most disturbing at speeds slightly off normal. By processing the playback signal it is possible to remove most of this impairment. The processing consists of the use of a vertical interpolator.

As noted before, odd and even fields differ only in that they are offset vertically by one raster line (one half field line). An odd field can be made into an even one by shifting it vertically by one frame line. This can be done by vertical filtering or interpolation. One simple vertical interpolator does this shift by averaging adjacent lines of a field with equal weight. The spatial center of this average falls half way between the scan lines or directly on top of the other field, thus forming an estimate of it. The averaging process introduces some loss in vertical resolution which can be quite noticeable. Higher order vertical filters involving more lines can improve this at the cost of more complexity.

Variable Speed Processor as Used in Digital Time Base Correctors As shown in Fig. 83, the variable speed processing circuit is placed before the main memory and following the DOC. In this way, the processor receives dropout-free video data, which prevents the comb filter from spreading dropouts across two lines due to its line averaging property.

6.6 TIMEBASE CORRECTION OF COLOR-UNDER MACHINES (Trytko)

Special Properties of Color-Under Systems Tape machines employing color-under techniques of recording are capable of providing a video signal which can be monitored directly without the use of a timebase corrector. To provide this ability, it is necessary that the chrominance information be retrieved in a manner which provides a color subcarrier sufficiently stable to lock a local oscillator. This creates an output color subcarrier which is not coherent with horizontal sync. Therefore, the video output of these tape machines cannot maintain an accurate sync-to-burst relationship and cannot be considered in accordance with FCC rules and regulations. Although a high quality picture can be obtained by viewing this signal on a color monitor, time base correction is still required to reestablish a coherent sync-to-burst relationship. The type of timebase correction required for color-under systems is therefore different from that of a direct color system. It is important to recognize the distinction between the color-under signal and the direct-color signal.

In a direct-color signal, the same timebase error exists in both the luminance and chrominance components. The burst-to-sync relationship therefore remains coherent and the timebase error of the composite signal can be characterized by a single error profile. Since both components (luminance and chrominance) of the video signal possess the same instability, measuring and eliminating the instability in one component will eliminate the instability in the other. Typically, the error information of the composite signal is determined from the chrominance information; the variation of burst zero crossings is generally accepted as the most accurate representation of signal instability.

In a color-under system, the heterodyne process substantially reduces the noticeable timebase error from the chrominance component. This creates a video signal which is made up of relatively stable chrominance encoded with relatively unstable luminance. As a result, each component of the video signal now contains its own timebase error profile. The timebase corrector, therefore, must stabilize two noncoherent and uniquely unstable components into one coherent composite video signal.

6.7 TBC Methods for color-under Systems (Trytko) The most straightforward method of accomplishing timebase correction of color-under signals is to treat the luminance and chrominance components individually (see Fig. 93). After separating the two components, independent error measurements can be made and used to correct the respective instabilities. Once the timebase errors have been removed, a stable and coherent composite signal can then be reconstructed.

A second and more cost effective method of timebase correcting a color-under signal involves the reconstruction of the noncoherent color-under signal into a composite signal which is essentially coherent (see Fig. 94). Apart from circuit complexity, the advantage of this method is that it easily facilitates color-under processing using timebase corrector configurations whose primary function is to stabilize direct color signals. The key to accomplishing this second method lies in the recognition that the instability on the tape machine output color subcarrier is small. This condition is guaranteed by the requirement that the video signal be viewable on a color monitor without requiring timebase correction. To do this, the output color burst must be capable of phase locking a crystal oscillator that can be used to

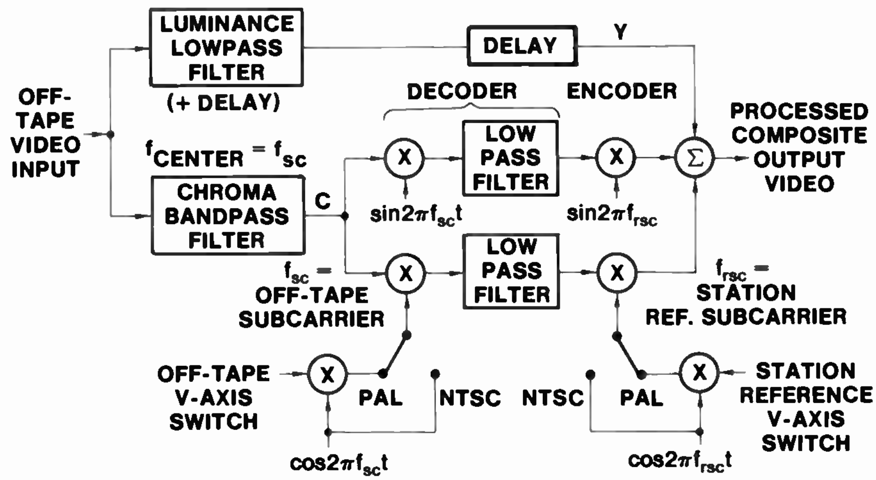


Fig. 91 Basic Chroma Processor

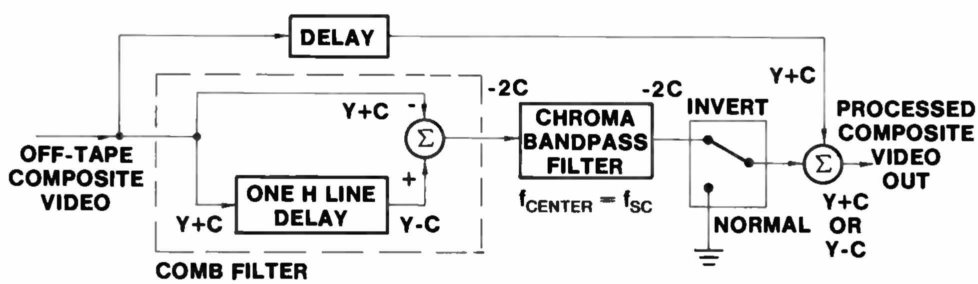


Fig. 92 Comb Filter Based Chroma Processor (NTSC)

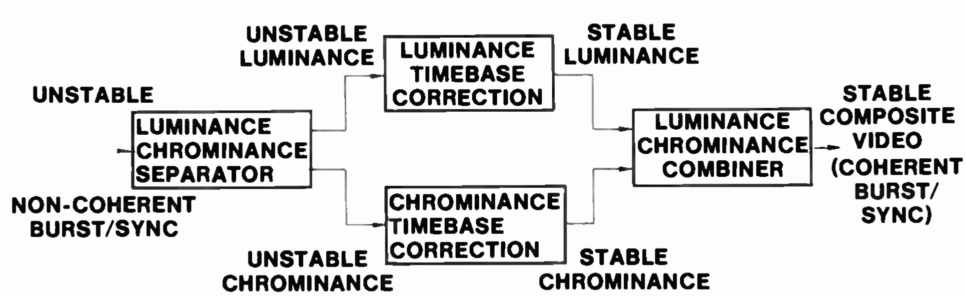


Fig. 93 Timebase Correction of Color-Under Signals

demodulate the chrominance information. Therefore, the timebase corrector can be made capable of performing this demodulation just like any color monitor.

At the same time, the timebase corrector can lock its VCO input clock to the incoming horizontal sync, which has the same timebase error profile as the luminance component. A sync-coherent color subcarrier can then be derived from this input clock and used to remodulate the demodulated color quadrature components. The timebase error profile of this resulting color subcarrier now resembles that of the incoming luminance information. By combining these two components, an unstable but essentially coherent composite video signal is created. This method, therefore, has effectively simulated a direct color signal from a color-under signal.

When reviewing the above system operation, it becomes apparent that separate encoding processing in the color-under machine and in the timebase corrector is not required. The decoder in the color-under machine utilizes a relatively stable subcarrier reference to be able to color-lock a monitor. However, this *stable* encoding process is of no use to the timebase corrector. In fact, it requires the timebase corrector to perform both a demodulation and re-modulation process in order to effectively encode the chrominance information using the sync-coherent subcarrier.

If it is known that the output of the color-under machine is to be fed into a timebase corrector before being viewed on a color monitor, then the requirement of *stable* chrominance at the tape machine output is no longer necessary. As long as the chrominance is stable at the output of the timebase corrector, the stability of chrominance at the output of the color-under machine is insignificant. The encoder in the machine, therefore, need not be referenced to a stable subcarrier. Specifically, there is no reason why the onboard encoder of the color- under machine cannot be referenced directly to the sync-coherent subcarrier signal developed by the timebase corrector. By providing the sync-coherent subcarrier as an output, the timebase corrector can stabilize the signal without having to decode and re-encode the chrominance information. This method, shown in Fig. 95, more faithfully processes the chrominance, and a higher quality picture is obtained.

This improved method of chrominance processing is referred to as *two wire* operation in reference to the additional signal feed required between the color-under machine and the timebase corrector. The standard operation previously detailed is often described as *one wire* operation.

6.8 SYNCHRONIZERS (Busby) A synchronizer may be thought of as a time-base corrector having a correction range of one field or one frame. Furthermore, it cannot be assumed that the synchronizer has any influence over the average timing of the input video. The rate at which video is clocked in may be permanently different from the output rate. The purpose of a synchronizer is to accept inputs from uncontrolled sources such as an unservoed VTR playbacks, remote sources arriving by microwave, and satellite feeds, and so delay them that the output remains entirely synchronous with other sources in the studio.

In the case of data entering the buffer faster than it is being withdrawn, inevitably the buffer becomes full. In the case of slower input than output, a condition is reached in which even though there is stored data, data is being read out very shortly after having been written. In the first case, one field or one frame of video is not output at all, i.e., the accumulated difference between input and output rates is discarded a field or frame at a time. In the second case, it becomes necessary to repeat the field or frame just stored, while some more data is accumulated.

Frame synchronizers sometimes discard or repeat in one frame increments, as it is simple to implement. The jerkiness of motion at the time of adjustment is sometimes visible, depending on the picture content. This effect can be lessened by adjusting only one field at a time.

Whenever a field is repeated, or one omitted, the normal odd-even progression is disturbed, and it becomes necessary to synthesize a field that by all appearances, preserves the sequence. Means to do this

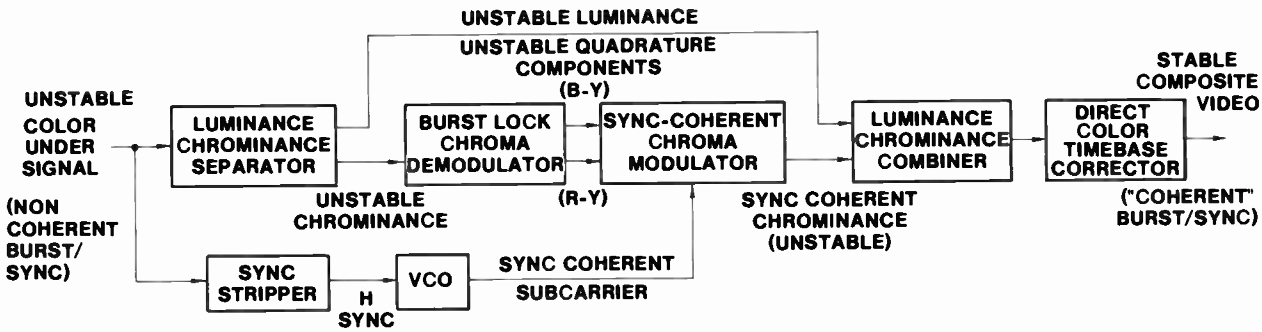


Fig. 94 Interactive Timebase Correction of Color-Under Signals (One Wire Operation)

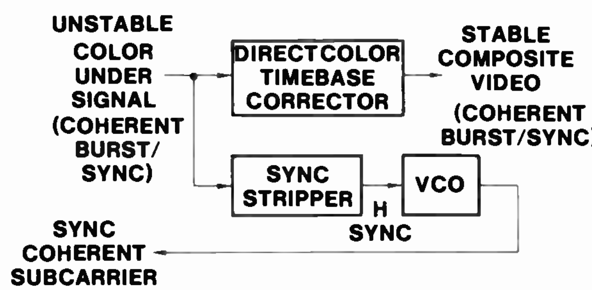


Fig. 95 Time Base Correction of Color-Under Signals by Direct Color TBC

is discussed in detail in the preceding section on variable speed playback.

When a field synchronizer is serving the dual function of synchronizer and timebase corrector, it can occur that around the point of decision to repeat or discard a field, the simultaneous presence of time base error can cause multiple conflicting decisions and disturb the picture. Hysteresis is usually applied to the decision circuitry in this case to minimize the effect.

A frame synchronizer, lacking any input at all, will present the last good frame stored within it, offering *freeze frame* when done deliberately. A field synchronizer can do this too, but with reduced vertical resolution and with the feature of fewer artifacts arising from motion in the picture at the instant of capture. This feature is sometimes used at the end of a tape playback when a few more seconds of video are needed, and a still frame is an appropriate filler.

7. VIDEO HEAD ASSEMBLIES AND SCANNERS

John W. King, Dennis Ryan

7.1 THE QUADRUPLEX HEAD ASSEMBLY (King)

Description and Functions The video headwheel panel records and reproduces the video and control track portions of the quadruplex format. In addition, it generates tachometer signals that are used to servo the head wheel motor, to provide video switching information and to generate the major component of the control track signal.

The headwheel panel is a compact sub-assembly that plugs into the tape transport and is secured by three screws. This permits quick and easy removal, and replacement by a spare assembly, when the panel is to be returned to the factory for refurbishing.

Figure 96 shows a typical headwheel panel. The unit shown is a Mark XV assembly used on the Ampex AVR-2 machine. Each headwheel panel has its own high-speed motor to which the headwheel is directly mounted. Mounted at the opposite end of the shaft are the magnetic and optical tachometers. The motor is equipped with hydrostatic air bearings. Air at 50 lb/in^2 is supplied by a compressor located in the console. Air is introduced into front and rear bearing journals through small orifices around the circumference of the bearing and is exhausted out the ends against the headwheel and the magnetic tachometer disc that serve as thrust bearings.

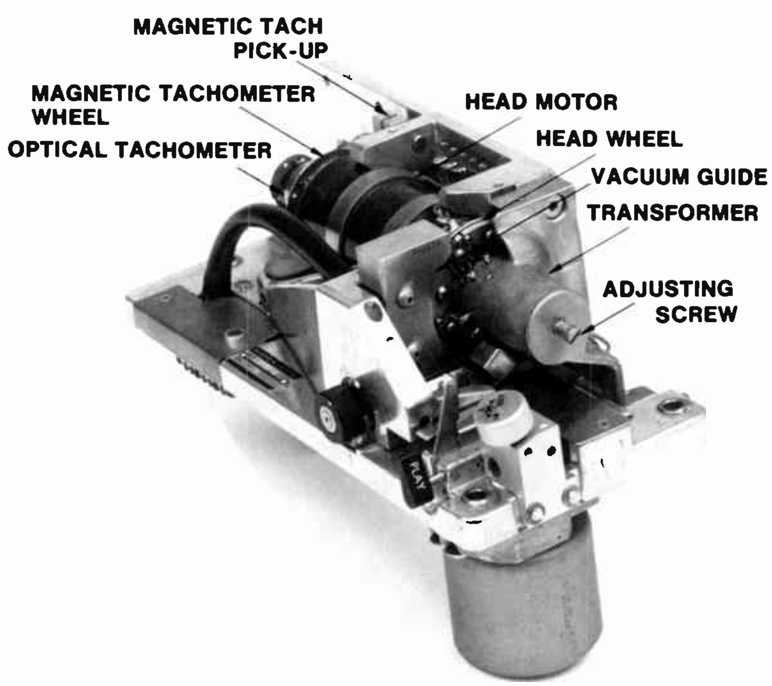


Fig. 96 Ampex Mk XV Video Head Wheel Panel

The headwheel, Fig. 97 consists of a stainless steel disc about 1/4 in thick and 2 in. in diameter. On its face are mounted four transducer assemblies spaced 90° apart. Each transducer assembly is made up of a shoe to which a tip, made of high-permeability, wear-resistant material is mounted. The tip contains the magnetic recording gap and windings and is the only part that contacts the tape. Each transducer assembly must be adjusted radially and circumferentially (this pertains to the head quadrature adjustment) to a high degree of accuracy. A tapered, eccentric pin extending into a hole in the headwheel provides the radial adjustment. Quadrature (circumferential) adjustment is accomplished by means of segments which are attached to the face of the drum between the transducers. The segments are slotted to provide thin sections at each end. One end serves as a spring that is compressed when the unit is assembled, so that it exerts a force against the adjacent transducer which pushes it against the segment on the opposite side. At the other end of the segment, the slot is spanned by a threaded hole which accepts a tapered screw. By loosening the transducer hold-down screw and adiusting the tapered screw, the transducer can be made to rotate around the tapered pin, moving the tip around the circumference of the headwheel. After adjustment the hold-down screw is tightened. Since spring pressure always exists against the transducers, backlash is eliminated, and very accurate adjustments can be made. Properly adjusted, the tips should project above the rim of the headwheel about .003 inches when new, and should be separated by exactly 90°.

The vacuum guide, Fig. 98, plays an important role in controlling the head-to-tape interface. When vacuum is applied to the two slots located on either side of the guide centerline, the tape is drawn in snugly against the radiused surface of the guide. A relief slot, located in the plane of the rotating tips, allows space for the tips to stretch the tape past the surface of the guide, insuring that intimate contact is maintained between tips and tape. The guide is movable, being switched between the operating and retracted positions by the guide solenoid. In the retracted position, the tape is pulled clear of the tips, which eliminates unnecessary wear during shuttle and standby modes. The operating position of the guide is adjustable through a narrow

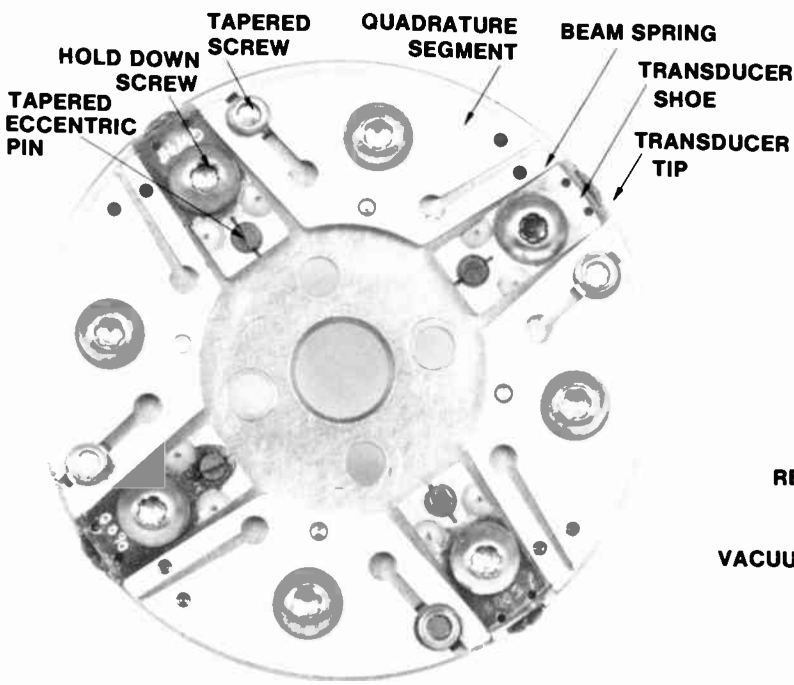


Fig. 97 Typical Head Wheel

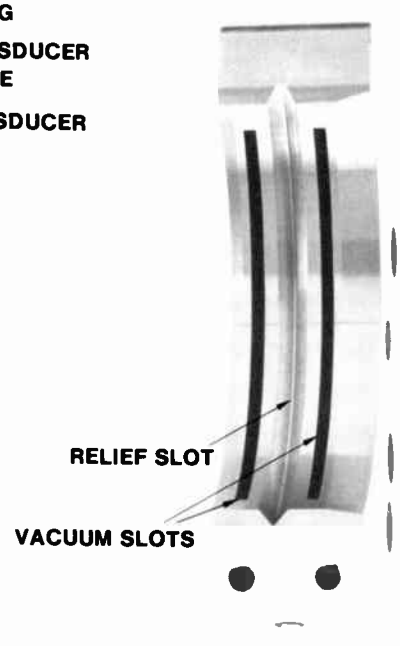


Fig. 98 Vacuum Guide Block

range, up or down and in or out, about the center of rotation of the headwheel.

The rotary transformer that conducts video signals to and from the transducers is made up of four pairs of ferrite cores each pair constituting an isolated transformer associated with its separate transducer. The rotating cores have a single turn winding connected to the transducers, and rotate in close proximity to matching stationary cores. Spacing between the rotor and stator cores is adjusted by a screw in the end of the transformer housing which also serves to ground the entire rotating assembly. Spacing between rotor and stator cores is adjusted to about .001 inch.

The control track head, which records and reproduces the control track and frame pulses at the bottom edge of the tape, is placed as close as practical to the headwheel to minimize the effect of tape stretch on tracking.

Figure 99 is a cross section of the vacuum guide showing the correct relationship of the headwheel, the guide and the tape in the operating position. Ideally, the center of rotation of the headwheel and the center of curvature of the vacuum guide should be coincident. Dimensions are chosen such that the guide radius exceeds the headwheel radius by .0014 inch, the thickness of the tape. The tips stretch the tape locally into the center relief groove, providing the intimate head to tape contact necessary to reproduce the required 100 microinch wavelengths. The distance that the tips protrude past the unstretched surface of the tape is termed *tip penetration*. It can be seen that the rim of the headwheel just grazes the surface of the tape, and serves to damp out oscillations that would otherwise be set up in the tape, causing erratic head to tape contact.

The same video signal is fed to each of the four transducers through its associated transformer during the record mode, and each transducer records across the full width of the tape. Some VTRs gate the record current to prevent disturbing audio tracks during video only recording. Subsequent erasure of portions of the video signal clears the tape for recording the longitudinal tracks. Some overlap remains, meaning that a small amount of information recorded by the transducer leaving the tape is duplicated by the following transducer as it enters the tape. During the reproduce mode, switching occurs during the redundant interval so that no information is lost. Switching takes place during the horizontal blanking interval, allowing the switching transients to be eliminated by subsequent signal-processing circuitry.

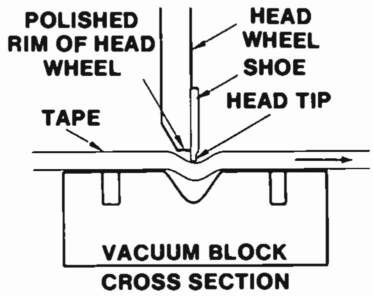


Fig. 99a Cross Section of Vacuum Guide

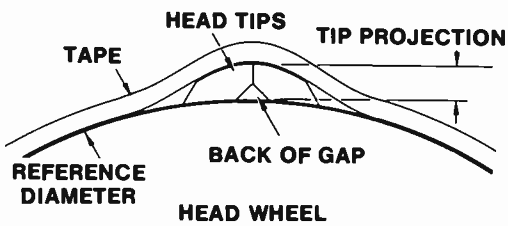


Fig. 99b Head-Tip-Tape Engagement Detail

Picture Geometry The geometry of the reproduced picture is sensitive to the positional relationship between the head and the guide. A recording made under the ideal conditions of Fig. 99 must be reproduced under identical conditions if geometry errors are to be avoided. Differences in position of 50 microinches or even less will result in noticeable time base errors in the reproduced picture. For this reason, provisions are made for making fine mechanical adjustments in the operating position of the guide. The results of incorrect guide position are illustrated in Fig. 100. While it is true that electronic time base correctors will compensate for a wide range of time displacement errors, good operating practice dictates that adjustments be made to produce the best possible uncorrected picture. It is interesting to note that the position of the vacuum guide need not be changed as the tip radius is reduced by wear, but remains the same throughout the life of the head tip. The amount of stretch that occurs in the tape due to penetration decreases as the tips wear down, decreasing the length of the tape traversed by the tip for a given angular displacement. The tip, however, having a smaller radius, travels at reduced tangential velocity so that equal amounts of information are scanned during the same angular displacement. This self-compensating feature permits establishing a unique position for the guide.

Additional geometry errors result from incorrect quadrature adjustment as well as imperfections in the vacuum guide. Figure 101 shows the effects of quadrature errors.

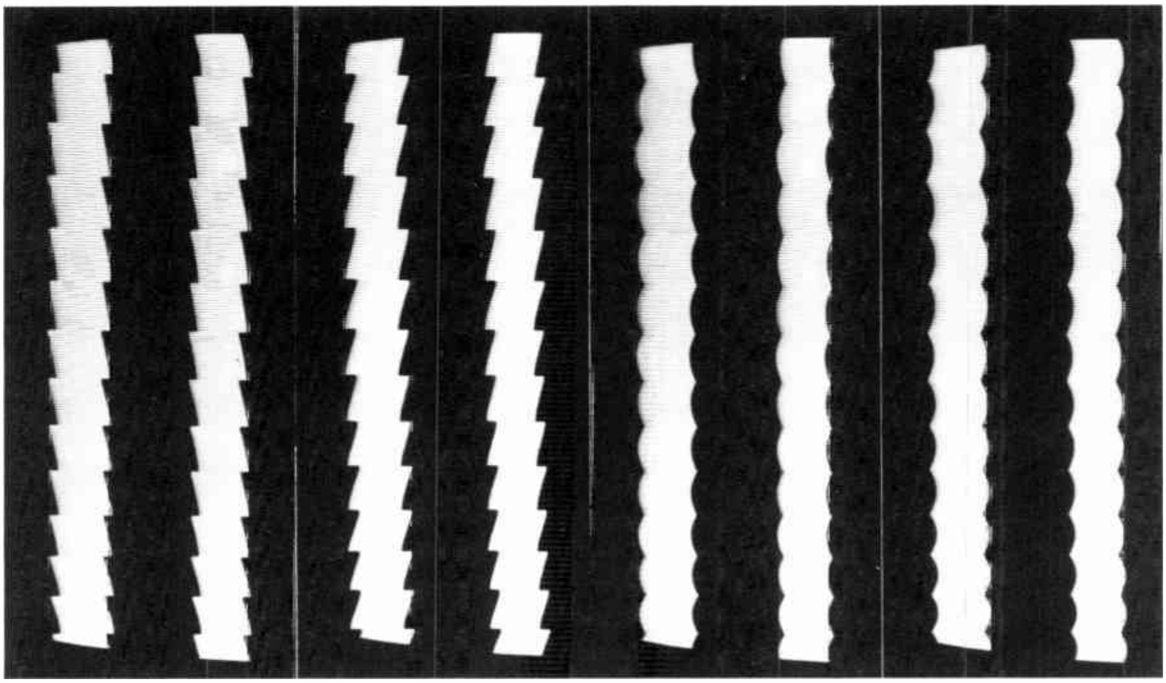
Evolution A review of the evolution of the headwheel assembly from its beginnings to its present state of sophistication may help to understand some of the problems inherent in the quadruplex recording process. It should be remembered that when the first quadruplex recorders were placed in operation, timebase correctors had not been invented, so that mechanical precision was essential to produce error-free pictures. To make a recording and reproduce it with the same headwheel assembly is a relatively simple process. As long as the machine is adjusted such that each transducer reproduces its own recorded track, mechanical displacement errors introduced in the record mode are cancelled during the reproduce mode. The requirement for interchangeability among different headwheel assemblies is a different story and requires high precision in the manufacturing process.

Early versions of the headwheel had no provisions for adjusting quadrature, so that it was virtually impossible to reproduce recorded tapes with a headwheel other than that which recorded it. During those early days it was not unusual for headwheel panels to be stored with their recorded tapes if future airing of the program was contemplated. Also, headwheel panels were shipped to other locations with the recorded programs for satisfactory playback. This was a costly and cumbersome procedure and acceptable only as a stop-gap measure. Two solutions were developed to circumvent the quadrature problem. A means of adjusting the 90-degree relationship among the transducers after final assembly was devised. The method made use of tapered screws and was similar to that used on present-day assemblies. By making a recording and reproducing it so that each transducer reproduced the information recorded by one of the other transducers, it was possible to deduce from the picture which transducer had to be moved, and in which direction. The headwheel was stopped and the appropriate tapered screw was adjusted. Another recording was made and the process repeated until quadrature errors were reduced to acceptable limits under all combinations.

Another method made use of delay lines in the record channels. Nominal time delays were introduced into each channel and a recording was made. If the recording was played back with the machine adjusted so that each transducer played a track recorded by another transducer, then the amount of positive or negative delay adjustment required to make a recording with minimal quadrature error could be estimated. Using these methods, acceptable interchangeable monochrome pictures could be produced.

The first headwheel panels used hysteresis synchronous motors with ball bearings. The ball bearings proved to be a major source of trouble. Even the slightest imperfection in races or balls caused a non-synchronous time-displacement error which traveled up or down through the picture. The phenomenon, known as *waterfall,* was eliminated with the introduction of the air bearing in 1963, which represented a significant step forward in the state of the art.

The first assemblies used sliprings to conduct video signals to and from the rotating transducers. Dirty sliprings and worn brushes were a common cause of transient noise that often occurred at such inopportune times as during the airing of an important network program. Considerable



A. GUIDE TOO FAR OUT B. GUIDE TOO FAR IN C. GUIDE TOO HIGH D. GUIDE TOO LOW

Fig. 100 Vacuum Guide Position Errors

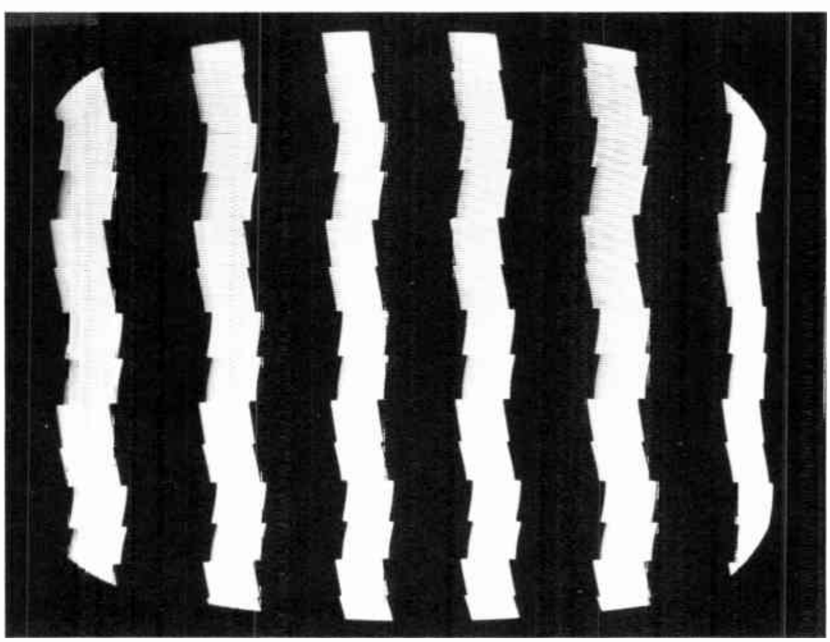


Fig. 101 Effect of Quadrature Errors on a Reproduced Picture

maintenance was required to keep sliprings and brushes in good condition. The rotary transformer introduced in 1962 proved to be the solution to the slipring problem and produced yet another major improvement in picture quality and machine reliability.

Soon after video tape recording became a reality, the Society of Motion Picture and Television Engineers assumed an active role in establishing industry standards. Dimensions and tolerances necessary to insure interchangeability were published as SMPTE recommended practices. A standard reference tape was developed that allowed all headwheel panels to be adjusted at the factory to conform to published standards, and thus to provide interchangeability.

7.2 HELICAL SCANNERS (Ryan)

General Helical scan recording provides a practical means of achieving the high head-to-tape speeds necessary for videotape recording and playback. Instead of forming the tape into a concave shape to mate with transversely rotating heads, as in the quadruplex system, the tape is wrapped convexly around the surface of a cylindrical drum, containing either a centrally located rotating head panel or a rotating upper half to which the head tips are mounted. By inclining the tape so that it wraps the drum in a helical fashion, the tracks are laid diagonally across the tape. The angle of inclination, or *helix angle,* determines the width of tape occupied by the video tracks, and the tape motion establishes the spacing, or pitch, between adjacent tracks.

Types of Helical Configurations There are two major categories of helical scan recorders: field-per-scan types, and segmented scan types. In field-per-scan systems, one video field (262.5 horizontal line in NTSC or 312.5 lines in PAL or SECAM) is recorded on each track. Segmented scan systems, like quadruplex recorders, record only a part of a field on each track, usually a half or less.

Within these categories are also found two common types of tape wrap configurations: full-wrap (or near-360° wrap), and half-wrap (or near-l80° wrap) systems. In practice, the wrap angle of a full-wrap scanner is lightly less than 360° to allow for tape threading and the placement of entry and exit guidepins. That of a half-wrap scanner is slightly greater than 180° to provide some overlap, or redundancy, between the entering and exiting heads. Figure 102 shows the scanner configurations mentioned.

In a full-wrap, field-per-scan system the head panel, or upper drum half, rotates at field rate (60Hz for 525-lines systems, 50 Hz for 625). There is a short dropout, or loss of information, which occurs while the video tip traverses the gap between the tape-drum tangency lines. This dropout can be timed to occur during the normally unused portion of the vertical blanking interval. In the 1-inch Type C format, an optional sync channel is provided to eliminate this loss of information by use of another head tip located below and in front of the video head, which is switched on only during the dropout period, resulting in a short *sync track* below and ahead of the corresponding video track.

In a half-wrap, field-per-scan system the upper drum half rotates at one-half of field rate (30 Hz for 525, 25 Hz for 625), such that one field is recorded during 180° of rotation. A second video head, located diametrically opposite the first, records the next field. The signal is switched between the heads during the brief period when both are in contact with the tape, such that no dropout occurs.

Since the writing speed is directly proportional to the drum diameter and the rotational speed, a half-wrap drum must be twice the diameter of a full-wrap drum for a given writing speed. This is the principal advantage of the full-wrap approach. The half-wrap, on the other hand, is easier to thread and is used almost universally in cassette-loaded systems.

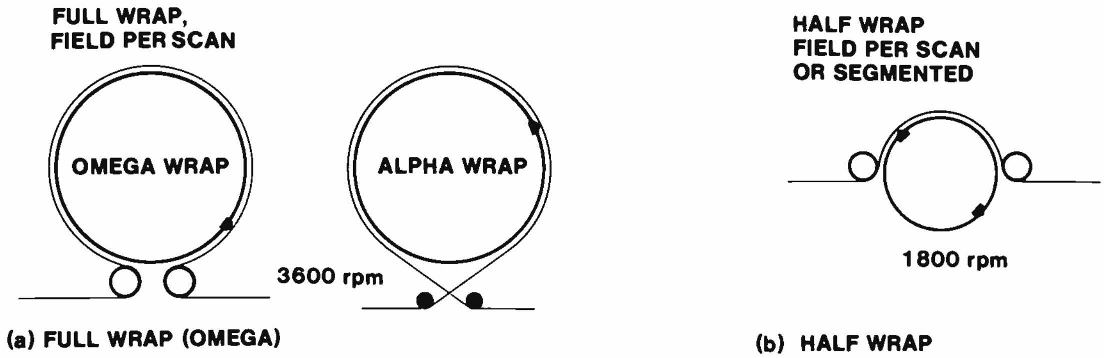


Fig. 102 Typical Helical Layouts

Segmented scan systems have the flexibility of using any integral number of segments or tracks to comprise one video field. If the number of scans per second is chosen as a common multiple of 50 and 60 Hz, (as in the Type B format, which is a half-wrap, 150 rev/s, or 300 track/s, system), then drum speed remains the same in both 525 and 625 versions, and there is no difference in writing speed. Another basic advantage of segmented scan systems is that small diameter scanners can be used with no penalty in writing speed, enhancing portability. The major disadvantages include the danger of banding in the picture, as in the quadruplex system, and the inability to produce slow motion, stop motion, and reverse play pictures without complicated electronic buffering.

Geometry & Format The direction of helix of the tape around the scanner may be either left-hand or right-hand, using terminology borrowed from screw thread convention. In a right-hand helix, such as the Type C format, the scanner rotates in a clockwise direction, viewed from above, and the tape rises in a counterclockwise spiral. In a left-hand helix, the scanner rotates counterclockwise and the tape rises in a clockwise spiral. Thus, for reasons to be discussed later regarding air film, the head always scans from the bottom of the tape toward the top, i.e., it begins the scan where the tape is highest on the drum and ends the scan where the tape is lowest.

The direction of tape motion relative to scanner rotation depends on other design parameters, which will be discussed subsequently. In the Type C format, (Fig. 103) the tape moves opposite to the scanner, thus adding the component of longitudinal tape motion to that of the head and generating a track angle shallower than the helix angle. In most auto-threaded cassette recorder formats, the tape is moved in the same direction as the scanner surface to avoid problems in threading and unthreading tape with the drum rotating. Here, the tape motion component subtracts from the head motion, and the track angle is steeper than the helix angle.

Figure 104 shows the configuration of the tracks recorded by a) a right-hand helix with tape motion opposite to the head, and b) a left-hand helix with tape motion in the same direction as the head, viewed from the magnetic oxide side of the tape All but a few video tracks have been omitted for clarity. Line H represents the path of the head tip during one scan, and illustrates the plane of the head motion. The edge of the tape is inclined to this plane by the helix angle, θ_H. Line S represents the tape motion during one scan, that is, the tape speed divided by the number of scans per second (the field frequency for a field-per-scan system). Line T is the vector sum of these two motions and represents the track itself, inclined to the tape edge by the track angle θ_T.

This same figure helps to illustrate another important criterion for helical formats, known as *sync pulse line-up.* The divisions shown on the track line T represent horizontal video lines, each track containing 262.5 lines in NTSC, 312.5 lines in PAL or SECAM, per field. Because of overlap or dropout each track may contain a greater or lesser number of lines, and its active length will be increased or decreased accordingly.

Note that the recorded information is physically positioned so that the horizontal sync pulses are aligned with those on adjacent tracks. This insures minimum phase jump in H-sync pulse timing between tracks during still frame operation, and provides the best possible slow-motion picture without special accessories. This condition also eases the design of special accessories that provide full-quality slow and stop motion playback or picture-in-shuttle features. Because of the odd number of lines in a frame, the offset between adjacent tracks must equal an integer plus one-half number of horizontal lines such as 2.5 as shown in the figure.

Due to this sync pulse line-up constraint, the field-per-scan formats have a limited choice of parameters compared to the segmented scan formats. Consider, for example, the following list of video parameters:

1. Sync pulse line-up number
2. Video rise (the width of tape occupied by the video tracks)
3. Writing speed
4. Drum diameter
5. Tape speed
6. Track pitch
7. Track angle
8. Helix angle

The sync pulse line-up number is perhaps more fundamental than the others because it provides a quantifying constraint on other parameters, such as track angle. Selection of any two other parameters in addition to this one will determine the rest, and it is important that the choice of the three be prudent so that systems optimization of all the parameters will be achieved.

Typically, video rise will be established according to tape width and the requirement for longitudinal tracks, ie. audio, control, and time code. Writing speed, and thus drum diameter, will be established commensurate with required video quality and transport size limitations, and, as noted above, the sync pulse line-up number.

Figure 105 shows the path of the tape before and following its lines of tangency with the drum. As can be seen, the centerline of tape lies in diverging planes that are perpendicular to the tape and inclined at the helix angle, θ_H, above and below the plane of head rotation. The tape will remain in these planes of travel as long as it is wrapped about cylindrical guiding elements whose axes are perpendicular to the tape centerline. In some helical recorders, the supply and take-up tape reels and all other tape path components lie in these planes. However, it is more common to redirect the tape onto parallel planes, or onto a common plane as in cassette-loaded systems with coplanar reels. This can be accomplished by twisted tape runs between inclined cylindrical guideposts, by helically wrapped pins, conical posts, or some combination of these, arranged such that the centerline of the tape remains undeflected from its natural path. In doing so, it is also common to incline the axis of the scanner such that the plane of the cassette or tape reels is parallel to the plane of the deck, or top plate.

Tape Guiding Accurate tape guiding around the scanner drum is accomplished with some form of guiding element fixed to the stationary lower drum half, in conjunction with adjustable entry and exit guidepins. These guidepins may be mounted to the scanner assembly, mounted adjacent to the scanner, or may even be incorporated into the tape auto-threading mechanism. In any case, they are an integral part of the scanner guiding system.

Most modern helical scan systems use a continuous guiding surface on the lower drum half. An example of a non-continuous system would be the Ampex 1-Inch format, known as Type A, which was superceded by the Type C format in the mid-1970's. In this system the scanner guide is a cylindrical ceramic pin mounted perpendicular to the drum surface at the midpoint of the scan, which, being eccentrically mounted, can be rotated to adjust its position up or down. Both the upper and lower drum halves are the same diameter.

To align this system, it was necessary to use a standard tape made with the proper track curvature and the proper track positioning. Because of the difficulty in

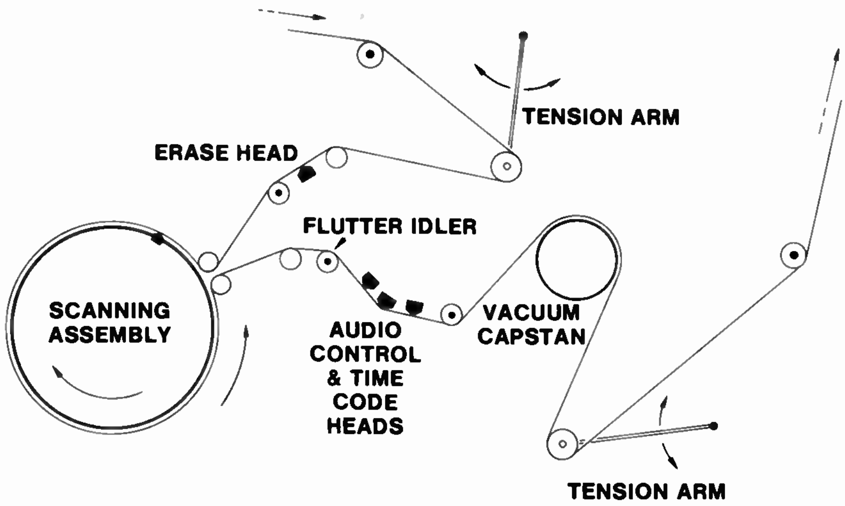


Fig. 103 Advanced Type C Format Transport

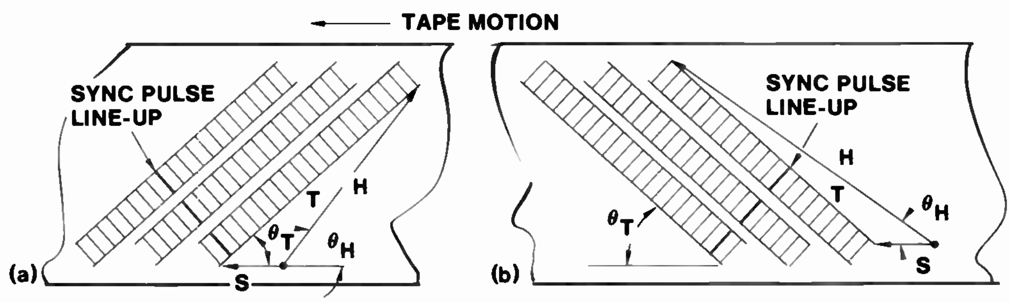


Fig. 104 Alternative Track Configurations

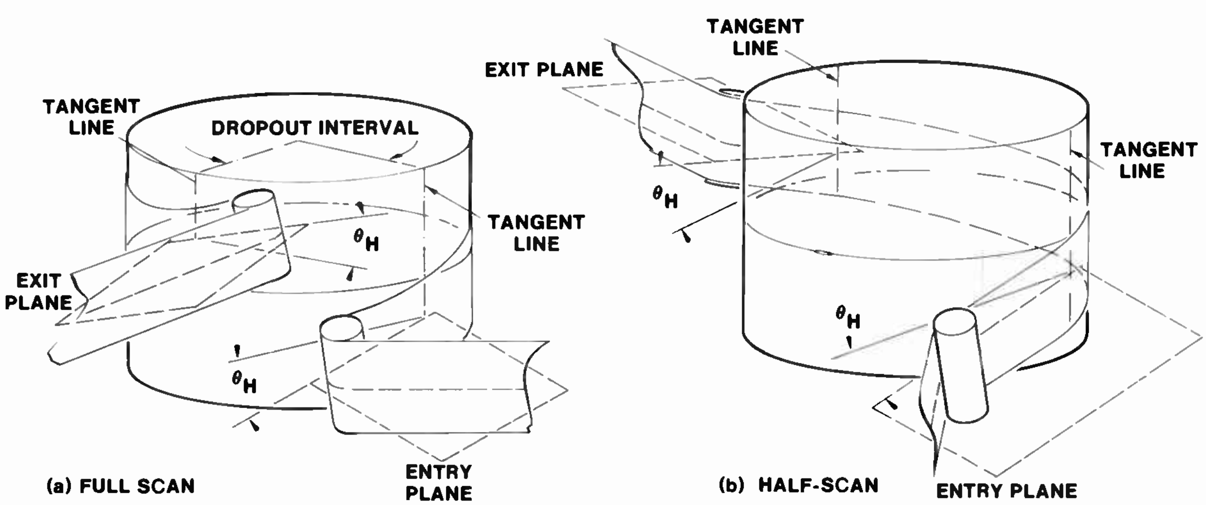


Fig. 105 Tape Paths

specifying and measuring the track geometry, plus the ability to misadjust the guiding and thus produce non-interchangeable recordings, it was superceded by the similar Type C format, using a continuous edge guide.

All standard helical formats intended for multi-manufacturer, universal interchange use, specify video tracks that are straight within very close limits, commensurate with the track width and the size of the track-to-track guard bands. These are achieved by registering the lower edge of the tape against a guiding surface that may be either a helically profiled step machined into the lower drum itself, or a separate band that is wrapped around the drum in a helical path and attached with screws at close intervals. In the case of the machined step, the scanner design may also provide a means of adjusting the bearings which support the shaft of the rotating head panel or upper drum, to eliminate runout with respect to the drum of the helical step. In the case of the separate band, the setting fixture may be referenced to the rotational axis of the shaft for the same reason.

The entry and exit guidepins have little effect on steering the tape against the edge guide beyond the first and last quadrants of wrap. Obviously, then, these guidepins have a greater influence on guiding tape in half-wrap systems than they do in full-wrap systems. Full wrap systems generally require some other means to bias the tape down against the edge guide during the remaining portion of the wrap. Some helical recorders with stationary upper drums use spring loaded ceramic pushers against the upper tape edge to achieve this purpose. For those systems requiring a rotating upper drum, such an approach would be impractical. In the Type C system, the diameter of the upper drum is made slightly larger than the lower, by 0.04 mm (0.0016 in), and this subtle difference is enough to cause the tape to slide down and register against the edge guide.

The wrap angle of the tape around the entry and exit guidepins must be sufficient to provide enough column strength to the tape so that guide adjustments will have the desired steering effect around the scanner. In half-wrap systems the tape path components adjacent to the scanner can be positioned so as to optimize this wrap angle. For full-wrap systems, the proximity of the two guidepins dictates a minimum wrap angle near 90° each, with a corresponding increase in tension buildup around the pin due to rubbing friction. In a typical Type C design, this might total 6 to 8 ounces of tape tension increase around the guidepins, while the increase around the drum itself is only 1 or 2 ounces. This is not necessarily a problem, except in the case of portable recorders requiring low power consumption, and thus lower drive motor torques, or in the case of high performance studio recorders which require lower tension buildups for bidirectional operation and rapid direction changes. In these cases, high-precision roller guides or forced-air lubricated guides help reduce guidepin friction.

To effect tape guiding, the guidepins are usually adjustable for both elevation and tilt in the plane of the tape between the guidepin and the drum. In addition, the guidepin-to-drum spacing and the angular orientation around the drum may be controlled to establish the length of the scan, or conversely, the length of the dropout interval, plus the location of the dropout interval. In addition, this spacing and orientation establish the location of the dropout interval, that is, the physical location of the ends of the track with respect to the tachometer-phased video information.

The guidepins may embody other usable features, such as being slightly conical or tilted towards the drum to locally increase tape tension and thus improve head-to-tape contact near the ends of the scan. They may contain other features to attenuate the tape disturbance effects associated with the head tips entering and leaving the tape.

Air Film With a rotating upper drum, a significant air-film is generated between the drum surface and the tape, minimizing tension buildup and stick-slip friction For this reason, all such helical formats scan from the bottom of the tape to the top, meaning that the tape is almost entirely on the upper rotating drum at the start of the scan, and the direction of head movement and thus drum rotation, act to pump air between the tape and drum. At this point the air-film thickness is at maximum, on the order of .001 in (0.03 mm). The film collapses to near zero at the end of the scan, where the tape is almost entirely on the stationary lower drum and the film is generated by tape motion alone. Variation in film thickness is non-linear because of the helical wrap, the effect of the gap between the drum halves, the pressure distribution under the tap and other geometric factors. Since the tape speed is relatively low compared to the drum surface speed, the direction of tape motion has little effect on air-film and is usually determined to meet other constraints, or in some cases may be bi-directional, such as in the reverse-play mode. In the Type C format, the tape moves opposite to the drum rotation in the normal record/play modes, which has the advantage of combining the outgoing or high tension end of the tape with the point of maximum air-film, where the head tip penetration is the lowest.

Grooving of the rotating drum surface can serve two distinct purposes. Deep grooves in the vicinity of the plane of the head tips have the effect of collapsing the air-film locally to improve head-to-tape contact. Shallow grooves are sometimes cut near the center of the rotating drum to channel the air and reduce the problem of *wringing* or *adhesion* if the tape is tensioned around the drum prior to start-up.

Number of Heads The number of rotating heads used in a helical scan system can vary from one (record/play) to three (separate record, play, and edit erase) heads per channel in a full-wrap system, to twice that number, mounted in diametrically opposite pairs, in a half-wrap system. The Type C system, being a full-wrap two channel system, uses six heads. The sync channel head is activated just prior to the dropout interval, and remains so only during that interval.

Most other direct-recording video systems are single-channel type. Recent developments in upgrading one half-inch half-wrap helical systems have resulted in two-channel formats using separate luminance and chrominance component signals recorded on parallel tracks.

On some half-wrap formats, the azimuth of the diametrically opposite head pairs are radically different to minimize the effect of one head infringing on an adjacent track during playback. This *azimuth recording* permits the reduction or elimination of inter-track guard bands for maximum utilization of the tape.

Scanner Construction Aluminum is the preferred material for scanner drums, because of its light weight, machinability, and dimensional stability. It has the additional advantage of having a coefficient of thermal expansion very near that of polyester-based videotape, thus minimizing timebase errors when playing back tapes over a wide temperature range. Drums have been successfully produced from wrought, forged, die-cast, and gravity cast processes.

Despite the advantages of design flexibility, low tooling investment, and good density and uniformity, turning drums from bar stock is usually avoided for two reasons. One is the high cost of machining. The other is problem of surface condition due to grain orientation within the bar stock, which can adversely affect friction characteristics and air-film at the tape interface.

Forged drums are common, particularly in the consumer recorder market, and have the advantages of high density and low waste. Disadvantages include high tooling costs, and possibly the grain structure problems alluded to above. Diecasting is attractive because of minimum machining, and permits more complex details to be cast-in. Material cost is low, but tooling cost is high. The choice of alloys is restricted, and the biggest problem is the control of microporosity and segregation of alloying elements on the drum surface. Gravity cast drums can be made more uniform, with lower porosity and from wider choice of alloys. Part costs are higher than diecastings, and require more machining.

The tape-contacting surface of the drum must be finished to a smooth and highly controlled condition. Some manufacturers send drums out for use in the as-machined condition, while others prefer an anodizing treatment to increase longevity.

Both the machining and finishing processes involve proprietary techniques developed through each manufacturer's experience and testing.

On rotating upper drums, the head tips protrude through windows in the drum face or through notches in the lower rim. The amount of *protrusion*, or *tip projection*, is carefully controlled to about 0.0032 in (0.08 mm). The head tips themselves are mounted to carriers or shoes that, in some designs, are factory adjusted and permanently fixed to the upper drum. In other designs, the tip adjustments are made within the shoe, which in turn is very accurately positioned with respect to the drum so that the shoe may be individually removed and replaced in the field.

In addition to tip projection, the azimuth of the gap, head elevation, and angular location of each tip must be accurately controlled. Azimuth is normally specified as perpendicular to the plane of head motion, except for *azimuth recording*, mentioned previously. Because of tape motion, the azimuth is not actually perpendicular to the track itself.

Head elevation establishes the track location with respect to the lower reference edge of the tape via the edge guide on the lower drum. In the Type C format the elevation of the record and playback heads are the same since the drum is rephased (120°) to interchange these heads between record and playback modes. The edit erase head is positioned 120° ahead of, and one third of a track pitch higher than, the record head to follow the same path when both heads are functioning simultaneously. There is a similar relationship between the three sync channel heads which are located on a lower plane so the tracks occupy a band beneath the video area and are switched off during the time when these head tips physically overlap the video track area.

The angular relationship between record, play, and edit erase head tips is critical, with tolerances of about ± 0° 5' of arc. The angular relationship between head tips which are *hot switched*, such as sync-to-video in Type C, or opposed tips in half-wrap systems, is much more critical since errors will result in step-errors in video timing. The same is particularly true for head switching in segmented scan systems. Here the angular tolerance will be about ± 0° 0' 15", which amounts to 0.2 μsec.

The shaping and contouring of the head tips involves a series of manufacturing processes designed to obtain the proper gap depth, the proper *footprint* on the tape for optimum contact, and a suitable radius of the edges so that no demagnetization occurs due to high contact pressure. During the first few hours of use the tips will continue to contour themselves to the videotape, conforming to its particular surface and base-film characteristics. This process will repeat whenever another type of tape is substituted. To obtain best performance it is always recommended that one type of tape be consistently used on a given scanner.

Signals to and from the video heads are brought out through rotary transformers, or on low-cost recorders, through slip-ring contacts. It is quite common to install playback preamplifier electronics and solid state head switching relays within the rotating upper drum with strict attention to the mounting of the components. As these are subjected to dynamic loads approaching 900 g's in a 60 Hz scanner there is a need for careful dynamic balancing.

Rotary transformers are generally the type using flat ferrite disc cores with windings fitted into shallow annular grooves. The gap between the rotor and mating stator is about 0.001 in (0.03 mm). In some designs the highly polished faces of the rotor and stator cores are lightly spring-loaded together and rely on the air-film generated by rotation to separate them. Most Type C scanners have six sets of rotary transformers, one for each video and sync head. Type C units equipped neither for the sync channel nor for the video confidence options may contain only two transformers, one for edit erase and one for both record and playback, switched internally.

Slip-ring and brush assemblies, even if not used for head signals, are commonly used to conduct power and control signals to rotating preamps, or to playback head servoes for automatic scan tracking. These may use a variety of exotic materials and alloys in both the ring and brush elements to improve wear characteristics, reduce noise, and provide low contact resistance. As a general rule, ring diameter is kept to the minimum to reduce surface speed, while still being large enough to provide mechanical rigidity and to accommodate the internal wiring of each ring. Brushes may either be wire wiper type or spring loaded plunger type, similar in principle to electric motor commutator brushes.

A common feature of helical scanners is a tachometer, usually a disc attached to the shaft below the drum interfacing with a stationary transducer. Optical encoding is typical, using slits in an opaque disc or bars printed photographically on a translucent disc, to interrupt a light beam focused on a photosensor. Other types include capacitive or magnetic coupling techniques.

The tachometer is accurately phased to the location of the video record head so that the angular position of the head tip can be detected and servoed during both record and playback. On some units the tachometer is also used to provide head switching information, as between the sync and video tracks of Type C. The number of tach pulses per revolution can vary from one pulse to several hundred, the higher resolution systems being common in portable recorders for improved scanner servo control during high angular inertial disturbances, and also in more sophisticated studio recorders.

High resolution optical tachometers are commonly used in conjunction with a matching stationary grating to shutter the light beam, or with some means of collimating the light source to prevent stray light from reducing the sensitivity of the system.

Most modern helical scan systems use a dedicated dc motor to drive the scanner, although in some systems the input torque is provided through a belt drive shared by other loads, with the scanner speed being regulated by a magnetic particle brake. On some compact recorders the scanner motor is detached and coupled through a polyester drive belt. However, in most professional recorders the motor is integral with the scanner assembly. Both brushless and brush-commutated dc motors are common, the pancake or flat rotor type being popular because of compactness, low cogging characteristics and ease of mounting and maintenance. Commutation of brushless motors may be incorporated into the scanner tachometer disc.

The rotating upper drum or head panel is coupled to the motor and tachometer through a shaft, usually stainless steel, whose high torsional stiffness places the torsional resonant frequencies well above any commutating frequencies or other periodic system disturbances. A tubular shaft may be used as a conduit for wire from the slip-ring and/or rotary transformers to head tips or preamp assembly. Ball bearings are commonly used, typically selected AFBMA Class 7 type, preloaded to reduce radial and axial play.

8. SERVO SYSTEMS

Harold Clark, Ray Ravizza, Reg Oldershaw

8.1 GENERAL (Clark) The components of videotape recorders referred to as the *servos* or the *servo systems* are synonymously defined as *feedback control systems.*

Videotape recorders, unlike audio or other stationary head tape recorders, have a rotating scanner, or headwheel, to achieve the high head-to-tape speed necessary for video bandwidths. It is then necessary to have at least one feedback control to coordinate the longitudinal tape motion with the rotating heads.

The servos used on videotape recorders may control rotary motion, as for example a rotating headwheel or capstan, or linear motion, such as the vacuum tape guide position on a quadruplex recorder. The variable controlled may be either velocity or position or a combination of both. Rotating components such as capstans or scanners are often operated in a *phase locked* mode, which from an analytical standpoint is analogous to a *position feedback loop.*

If the motor is driven by a current source, as is usually the case with a capstan motor, *motor torque* is the output quantity that is directly controlled by a voltage input to the motor drive amplifier. Any torque more than the constant or viscous friction loads on the motor will produce acceleration proportional to the excess torque. The angular velocity is the integral with respect to time of the angular acceleration. The shaft angle (phase) at any time is the integral with respect to time of the angular velocity. Thus, the phase output of the unit is the double integral with respect to time of the voltage input to the motor drive amplifier. This produces 180° phase shift of the feedback signal, so feedback is no longer inverse, but instead positive. The loop is therefore inherently unstable and will oscillate unless some phase correcting components are added to it.

On the other hand, a loop that feeds back velocity information only, without regard to phase, will nearly always be inherently stable without additional phase correcting circuits. A velocity loop may be added around the motor, within the phase lock loop, to provide the phase correction necessary to stabilize the phase lock loop. This combination has been used in several typical VTR servos.

The early quadruplex transverse scan recorders generally had three feedback control, or servo, systems -- a headwheel servo, a capstan servo, and a guide position servo. If an attempt were made to list these in the order of their importance to the function of reproducing a video signal from tape, the capstan servo would rate first place, followed by the headwheel servo, and then the guide position servo. A reproducible, although not standard, recording could be made with no control of the headwheel or capstan other than turning at a constant speed, and with the tape guide in a fixed position. To achieve even a limited playback, however, either the capstan or the headwheel must be under feedback control with reference to the other to assure that the transverse video tracks coincide in time of passing the guide shoe with the rotational passage of a video transducer on the headwheel.

In the interest of standardization and interchangeability, all tapes are recorded as uniformly as possible. In the record mode, therefore, the servos are dedicated to achieving a standard recording. The headwheel or scanner servo causes the start of a video field to be recorded at a precise position on the video tracks. The capstan servo causes the longitudinal tape speed to be accurately controlled, so the video tracks will be spaced to the standard dimension. Video track length is controlled on a quadruplex machine by accurately adjusting the vacuum tape guide to the standard position. On a helical machine the track length is controlled by accurately controlling tape tension in the record mode.

In the playback mode, the servo functions are similar, but generally oriented to synchronize the reproduced video to studio sync and to compensate for any departure of the recording from the centerline values of various parameters. One example is the action of the guide position servo in compensating for any error in positioning of the guide during either record or playback. Another is the function of the capstan servo in compensating for slight differences between the recording machine capstan diameter and the playback machine capstan diameter.

8.2 COMPONENTS (Clark)

Motors The earlier models of Ampex quadruplex recorders used a hysteresis synchronous motor for the headwheel drive. This type of motor operating in the synchronous mode required a variable frequency power amplifier to drive it. Since the motor shaft was phase locked to within the torque lag angle of the driving signal frequency, the parameters that had to be controlled were the frequency and phase of the driving signal. The motors were two pole, three phase designs, requiring 115V, 240 Hz, three phase drive power for 60 field television standards, or 115V, 250 Hz, three phase power for 50 field standards.

The drive frequency originated from a single phase voltage controlled oscillator. Since the system operated over a narrow range of frequencies, simple RC phase shift circuits were used to generate two signals 90° out of phase. This two phase signal was amplified by two linear power amplifiers to the required power level. To convert to three- phase power, the output transformers were connected in a Scott-T connection for two to three-phase conversion.

Later models used a three-phase power switching drive in which the power output transistors operated in a saturated switching mode for greater efficiency. The signal originated in a voltage-controlled oscillator operating at six times the output frequency. A three-stage ring counter triggered by the oscillator generated the three-phase switching waveforms for the power output stages.

Early RCA models used the same type of three phase motor, but operated in a sub-synchronous voltage-controlled mode. In this mode the motor output torque was proportional to the applied voltage as long as the motor ran below synchronous speed. See Fig. 106. The servo feedback controlled the applied voltage amplitude to control the torque and consequently the speed and phase of the motor. In this way the headwheel was phase locked to four or five times the reference vertical-sync frequency.

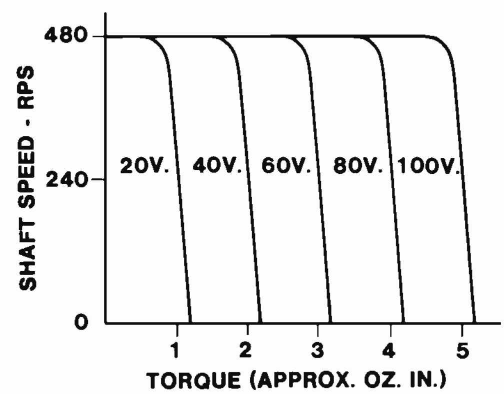


Fig. 106 Hysteresis Motor Operating Below Synchronous Speed

Later models, such as the Ampex AVR-1, ACR-25, AVR-2, and AVR-3, used brushless dc types of headwheel motors. These motors have simpler, more easily controlled characteristics and are generally more suited to semiconductor drive circuits.

Early model recorders also used hysteresis synchronous motors for the capstan drive. A two-phase dual winding design provided operation on 15 or 7.5 inches per second. One typical motor was a dual 6 pole/12 pole design. In either case the drive power was nominally 115V, two-phase, 60 Hz (or 62.5 Hz for 625/50 television standards) supplied from a two-phase motor drive amplifier.

The reel drive motors in the early recorders were 50/60 Hz, 115 Vac torque motors. The designs were high slip, capacitor split-phase induction motors. One winding was designed to operate with a series phase shifting capacitor to generate the required phase shifted drive. Torque was adjusted by merely raising or lowering the applied voltage with a variable series resistor. See Fig. 107.

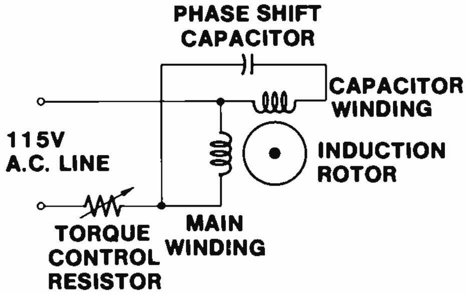


Fig. 107 A.C. Torque Motor Reel Drive Circuit

Later models generally used dc torque motors of one type or another. The Ampex AVR-1 used a series-wound motor with a silicon-controlled rectifier (SCR) drive circuit. The Ampex ACR-25 used a shunt-wound motor with an SCR drive. Still later machines have generally used permanent-magnet-dc or brushless-dc motors.

Tachometers Tachometers are employed on various rotating parts of VTRs to obtain a measure of the rotation - either velocity or phase. Optical or magnetic types are generally used. The first recorder used only a simple photoelectric cell pickup on the headwheel shaft. It consisted of a reflecting ring painted with nonreflecting black paint over 180° of its rotation, an incandescent light source illuminating the ring, and a photoelectric cell to receive the light from the reflecting surface. The signal output approximated a square waveform and was used for various purposes within the VTR. One use was for controlling the commutation of the four playback channels in the head switcher. The servo loop used the signal for phase and velocity information. Since the information was obtained only once per revolution, the feedback loop bandwidth was limited to only one-sixth to one-tenth of that information rate.

For higher bandwidth servos, multiple point tachometers are used. Optical tachometer discs with hundreds or even thousands of lines per revolution are used on higher bandwidth capstan servo loops. A high degree of accuracy, both in the manufacturing of the disc and its mounting on the capstan shaft, is necessary for low-flutter performance.

Magnetic pickup devices are also widely used as tachometers. Usually some form of variable reluctance device is used. Information rates range from one or a few pulses per revolution to hundreds of cycles per revolution on a *gear tooth* type of device. The latter sums the magnetic reluctance effect from all the points around the circumference simultaneously and thereby averages out any tooth-to-tooth inaccuracies. Considerable precision is still required in centering and elimination of wobble to avoid once-around disturbances.

8.3 HEADWHEEL SERVOS (Clark)

Record Mode In the record mode the headwheel servo of a quadruplex machine is designed to cause the vertical-sync pulses of the recorded video to be written in a location on the tape as specified by the industry standards for the television signal being recorded. See Fig. 108.

The basic headwheel servo functions for the record mode are illustrated in Fig. 109. The 60- or 50-Hz reference pulse is derived from the vertical-sync signal of the video signal being recorded. A timing point that is easily extracted is the trailing edge of the first wide pulse in the field synchronizing pulse sequence. Its timing accuracy will be that of the tolerance on the sync pulse width and will generally be consistent within 1 μsec. The headwheel tachometer once-per-revolution signal is phase-compared to the extracted vertical pulse once each fourth (or fifth) revolution of the headwheel to accurately position the time of writing vertical sync on the tape to within the specified standard. The phase comparison of signals with a 4/1 or 5/1 frequency ratio is easily accomplished with a sample-and-hold circuit in which the field-rate pulse samples every fourth or fifth cycle of a ramp signal generated from the once-around tachometer. Figure 110 illustrates the method.

Although the standards allow a tolerance of about 20 μsec peak-to-peak on the timing accuracy, good practice dictates keeping the error as small as possible. Three or four microseconds peak-to-peak, including fixed offsets due to mechanical adjustment tolerance, is readily attainable.

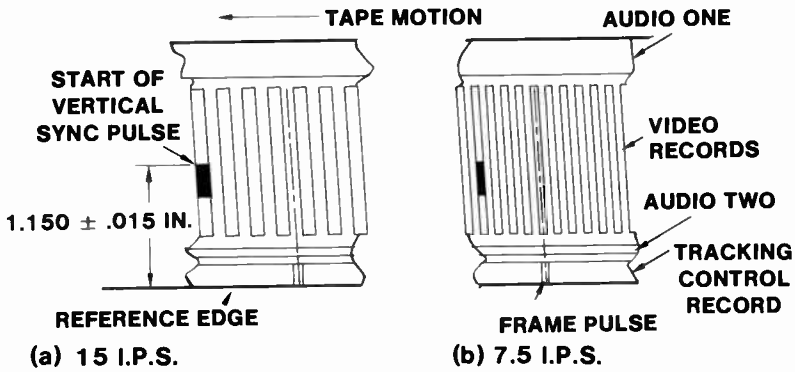


Fig. 108 Quadruplex 525/60 Format

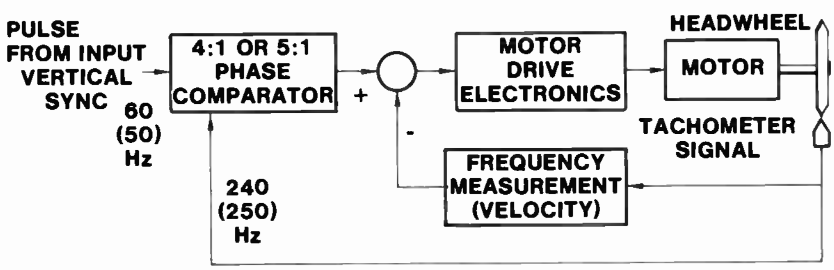


Fig. 109 Record Mode Head Wheel Servo

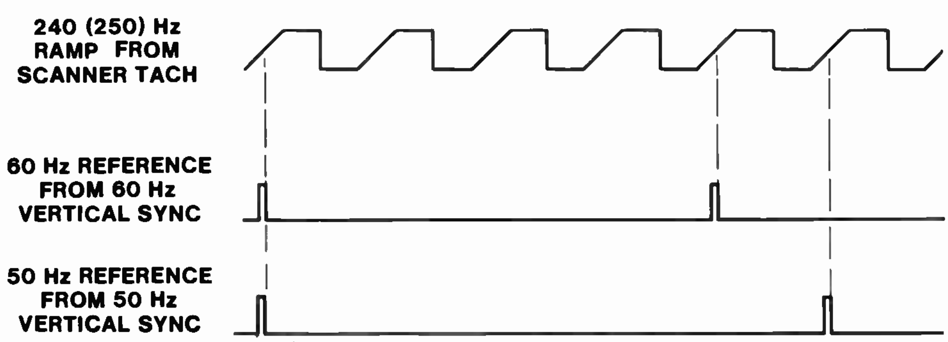


Fig. 110 Phase Comparison by Sample and Hold Circuit

Playback Mode In the playback mode, the headwheel servo determines the timing of the reproduced video signal. The basic function is similar to the record mode except that the reference signal is usually local-studio sync instead of sync decoded from input video. The reproduced video signal is timed so that the final video output from the TBC is in time with other studio video signals at the video switcher. The demodulator video output will need to be earlier than the studio reference sync by an amount that will keep the TBC operating about the center of its dynamic range.

Another playback servo mode, used on some recorders, involves *horizontal lock*. This mode compares the timing of horizontal sync pulses of the demodulated video signal with studio or other reference horizontal sync pulses. Because the feedback information rate is over 15 kHz, as opposed to 60 or 50 Hz with the other modes of operation, a much higher feedback loop bandwidth can be obtained. This results in a correspondingly smaller playback timing error of the demodulated video signal before electronic time base correction. Since the early TBCs had only one microsecond correction range, this mode was necessary to keep the timing error within the range of the TBC.

Later TBCs have much greater correction range, easing the requirement for tight servo control except for the case of electronic editing of tapes that may be played on a machine with a one microsecond TBC range. Because such use is likely, electronic editing of quadruplex tapes is nearly always done using horizontal lock to keep the edit point timing transient below one microsecond. A complete line- for-line and subcarrier phase match is needed to make a perfect edit, so the servo lock-up sequence involves first framing the playback to within one horizontal line of a correct line-for-line match of playback and reference video, including subcarrier phase, and then proceeding to lock on horizontal sync. Feedback loop bandwidths to 100 Hz or more are typical with horizontal lock, giving timing accuracies to within 0.2 microsecond. With field-rate sampling, 5 or 6 Hz bandwidth would be typical, and timing accuracies are correspondingly reduced.

8.4 SERVOS FOR HELICAL RECORDERS (Clark)

Record Mode Helical scan VTRs have similar requirements to those of quadruplex recorders. Figure 111 shows the basic functions of a 1" Type C format scanner servo. A Type C recorder in the record mode compares scanner once-around tachometer phase to input video vertical sync. In this way vertical sync and its associated blanking is positioned with respect to the scanning dropout region that occurs as a result of the Omega wrap format. The requirement is to record a tape meeting Type C format standards.

Playback Mode The helical playback mode, like the quadruplex playback mode, compares a tachometer once-around signal with a studio vertical-sync signal to time the final video output from the TBC with other studio video signals at the video switcher. The demodulated video output will require a timing advance equal to the average TBC total delay.

Another scanner playback-timing requirement occurs as a result of the use of separate record and playback heads. The playback head is displaced 120° from the record head, so the scanner must be phased 120° differently between the record and the playback modes.

Helical scanners can be servoed with off-tape horizontal sync in a horizontal lock mode. This was done on the Ampex VPR7900 recorder, but later Type C recorders such as the VPR2, VPR6, and VPR80, do not use the method because the wide dynamic range of TBCs now available makes it unecessary. The result is that the timing requirements on the servo are less stringent and reliability is increased.

8.5 CAPSTAN SERVOS (Oldershaw)

Control Track The purpose of the control track is to provide a record of the rotational position of the scanner, in the case of the helical recorder, (or the headwheel, in the case of a quadruplex VTR) as the tape passes the locus of rotation of the video heads during the recording process. At the same time, the reel-to-reel tape motion is servo-locked to the scanner (or headwheel) by the capstan. In playback, a tracking control is used to adjust the angular position of the capstan motor so that the previously recorded video tracks are centered on the paths of the rotating heads, to obtain the maximum playback voltage and the maximum SNR.

The control track signal is recorded near the lower edge of the tape by a fixed head. The record format showing the control track position on tape for helical Type C one inch tape, and quad two inch tape, is shown in Fig. 112.

In playback a longitudinal head placed a fixed distance from the scanner reads back the control track signal. One cycle of control track corresponds to one cycle of scanner rotation and an odd/even frame identifier is added. In Type C helical one inch recorders, one cycle of scanner rotation is one field. For quadruplex recorders, one cycle of headwheel rotation is one quarter field for 60 Hz systems, and one fifth field for 50 Hz systems. The record waveforms are shown in Fig. 113.

Motor Assembly At less than 50 oz in, the torque requirements of the capstan motor are modest. The tape path is designed to have nearly zero tension difference across the capstan hub to minimize creep between hub and tape. The torque requirements are comprised of the accelerative torque needed plus the frictional torque lost in the motor bearings. An important requirement of the motor assembly is uniform angular rotation at play speed. To achieve this, a motor having minimum brush/commutator or magnetic cogging is essential, and so a skewed armature motor or a multi-commutator printed circuit motor is used. To help still further, a small flywheel having an inertia of only .1 to .2 oz.–in.–sec^2 and a high resolution optical tachometer, are added to the capstan shaft.

The tachometer design is chosen such that at play speed the output is a multiple of the scanner rotation and so can be phase locked to an oscillator that in turn is phase locked to the scanner. For example, in the Ampex VTR models AVR1, AVR3, and ACR25, the tachometer frequency is 3840 Hz, 16 times the scanner frequency of 240 Hz. This forms the inner loop of the capstan servo that, having this high carrier frequency, usually has a bandwidth of 100 Hz to 200 Hz. The high resolution tachometer is also useful for maintaining adequate feedback information for slow speed search.

The capstan motor assemblies may include a pinch roller that holds the tape against the capstan hub and is engaged by means of a solenoid during the play and record modes. Capstans using pinch rollers have small shafts, under 0.5 in, and do not control the tape movement in high speed modes. In shuttle or search modes, the pinch roller is disengaged from the tape, and a low inertia tape idler having an optical tachometer meters the tape movement for displaying tape time and search-to-cue-point information. Since the capstan is only used in the play mode at a single speed, a flywheel is used having an inertia of 0.2 to .3 oz–in–sec^2.

Capstan assemblies that do not have a pinch roller have a larger hub diameter (up to 2 in) and use either a thin neoprene coating on the hub to prevent tape slip or a perforated surface with an interior vacuum manifold to hold the tape on the capstan surface. Where a pinch roller is not used, the angle of wrap required around the hub is approximately 180°. The capstan can be used to control both play/record modes and shuttle/search modes, information for the timer and search-to-cue circuits being provided by an optical tachometer on the capstan shaft.

Analog Capstan Servo In older video tape recorders in which the servos were completely analog, the playback loop was typically configured as shown in Fig. 114. The inner velocity loop had a bandwidth of 100 Hz to 200 Hz. The capstan tachometer signal after processing was applied to a frequency discriminator and compared to a reference signal that was 16 times the head tachometer frequency. Errors in capstan speed were amplified and applied as a correcting signal through the MDA to the capstan motor. This type of loop provided excellent damping and reduced commutator and magnetic cogging.

An outer position loop has a much lower bandwidth and provides the phasing

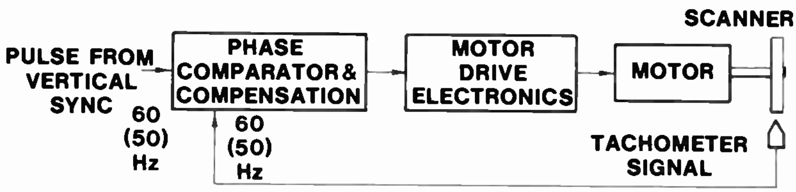


Fig. 111 Type C VTR Scanner Servo

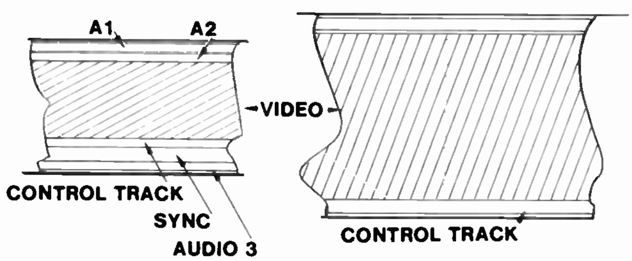


Fig. 112 Control Track Format on Tape

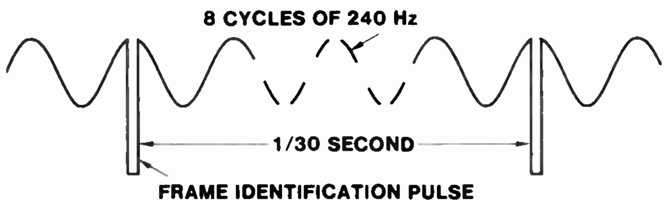


Fig. 113 a) Quad Control Track Record Waveform

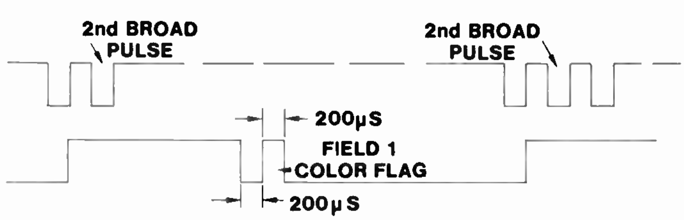


Fig. 113 b) Helical Control Track Record Waveform correction necessary to keep the video tips on the center of the recorded tracks. In a quad recorder operating on 60 Hz standards, the control track signal and headwheel rotational rate are 240 Hz and 240 rps, respectively, and the bandwidth of this loop is 10 Hz to 15 Hz. For one inch helical recorders the control track signal and scanner rotational rate are 60 Hz and 60 rps, with a loop bandwidth of approx. 5 Hz. Errors in phase between the input signals are amplified and summed with the velocity error to provide the necessary correction to the capstan motor.

In record, the control track phase comparator is switched out and a capstan tachometer phase comparator switched in, using the same input signals as the velocity loop frequency discriminator. This is to ensure that the capstan remains phased to better than one tachometer line of the high resolution tachometer.

Digital Capstan Servo In more recent video tape recorders, the extensive use of digital integrated circuits permits a capstan servo design that is more compact, and has less drift with time and temperature.

Figure 115 shows the manner in which this is accomplished using the same quad recorder example as Fig. 114. The loop compensation and MDA remain analog functions, but a tachometer-locked loop replaces the velocity loop of the analog example. Once again, this loop is a high bandwidth loop and has a phase comparator whose output is proportional to the difference in phase between a reference signal derived from the head tachometer and the capstan tachometer signal. When the input signals to the phase comparator exceed one cycle of the capstan tachometer, the output is forced to the limit voltage. This is the case during lock-up, and does result in overshoot, since full MDA power is applied until the capstan tachometer frequency reaches the reference frequency, the dynamic range of the phase comparator being only 180° of the tachometer rate. On new servos using microprocessors, this limited dynamic range is extended to ± 8 cycles of tachometer or ± 64 cycles of tachometer, and is discussed in Section 8.9.

Figure 116 shows one type of digital phase comparator using a *shift left, shift right* register in which only the first three stages are used. When tachometer and reference are equal in frequency, and when the two signals arrive in an alternating fashion, the middle section of the register toggles back and forth with a *mark/space* ratio equal to the difference between the two signals. If the tachometer frequency is lower than the reference frequency, then more *left clock* pulses arrive, and the output from the middle stage of the register remains high. If the tachometer frequency goes above the reference frequency, more *right clock* pulses arrive and the middle stage of the register remains low.

Shifting the phase of the capstan to place the video head tips on the center of the recorded video tracks is done by shifting the phase of the reference to the tachometer lock loop. This simply requires adding pulses to the reference clock stream to shift the phase in one direction.

In record the *add/subt* logic, is disabled, and the capstan is once again locked to the headwheel. For the larger shifts in phase required when matching off tape TV frames to studio reference TV frames, the reference signal to the phase comparator is switched to a fixed clock that is offset by the required framing speed offset, and then switched back once a frame match has been achieved.

Every effort is made to obtain the maximum gain and bandwidth from the available information rate. For this purpose, the filtering of the clocking signals (capstan tachometer, reference clock, control track, etc.) is done by a *sample and hold* method on a ramp instead of integrating over, perhaps, 10 to 50 cycles of tachometer signal, since this adds excessive delay to the loop. Figure 117 shows the method. Typically, the output of a digital servo is a flip-flop being alternatively toggled from tachometer and reference. One-shot #1 is fired by the reference edge and forms a delay to clamp the capacitor C_1 to ground. At the end of the delay period the capacitor is charged through a constant current generator to form a ramp. One-shot #2 forms a sample pulse for a sample-and- hold and the sample is held on C_2. The sample

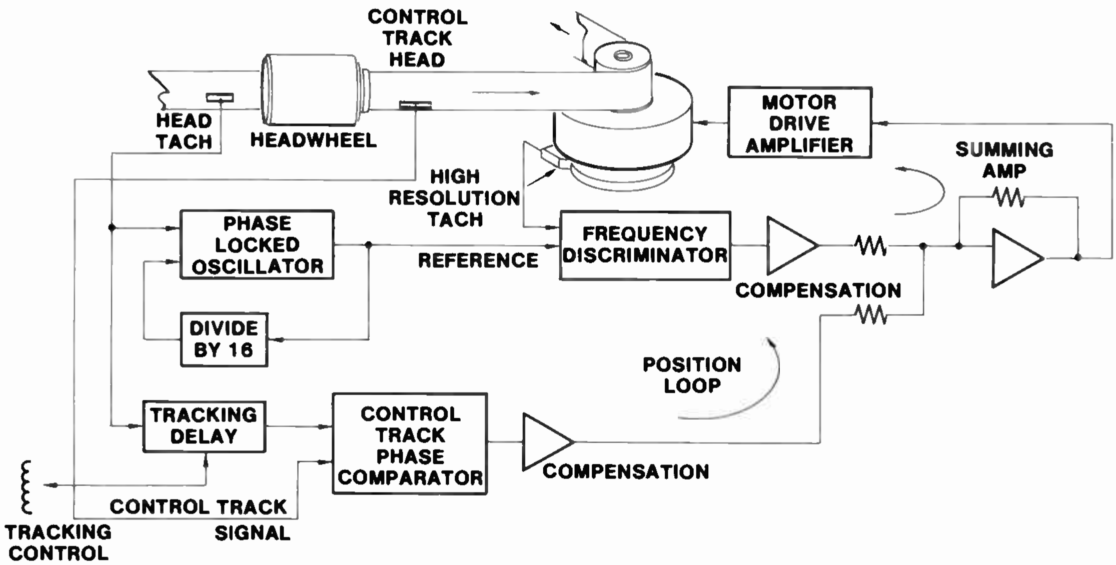


Fig. 114 Analog Capstan Servo for Quad

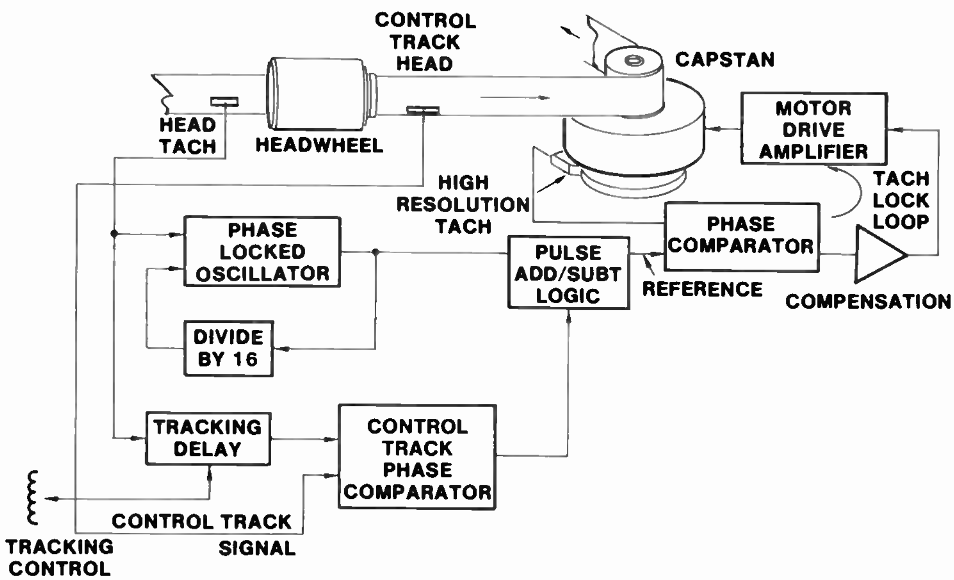


Fig. 115 Digital Capstan Servo for Quad

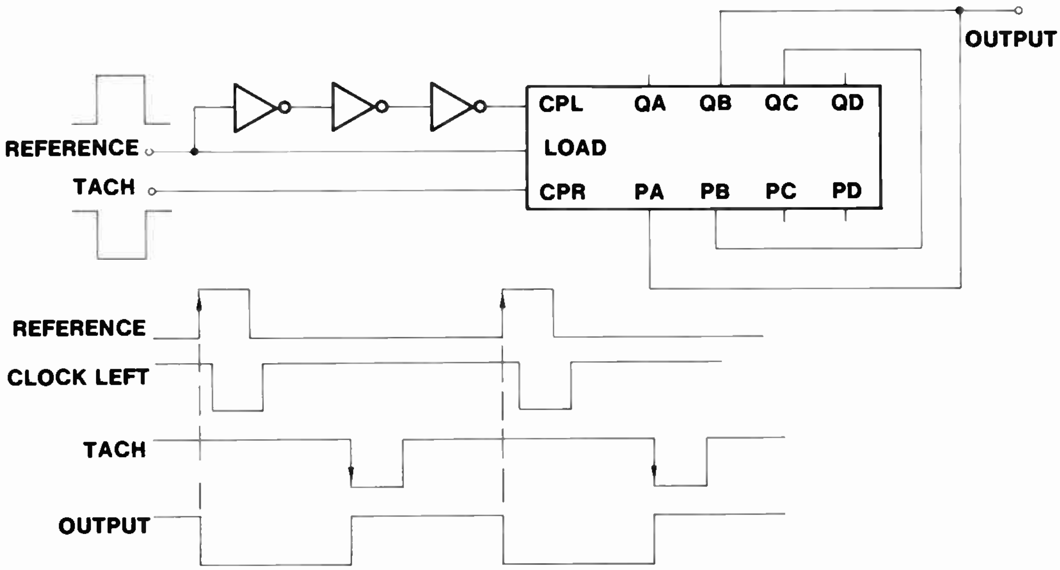


Fig. 116 Digital Phase Comparator

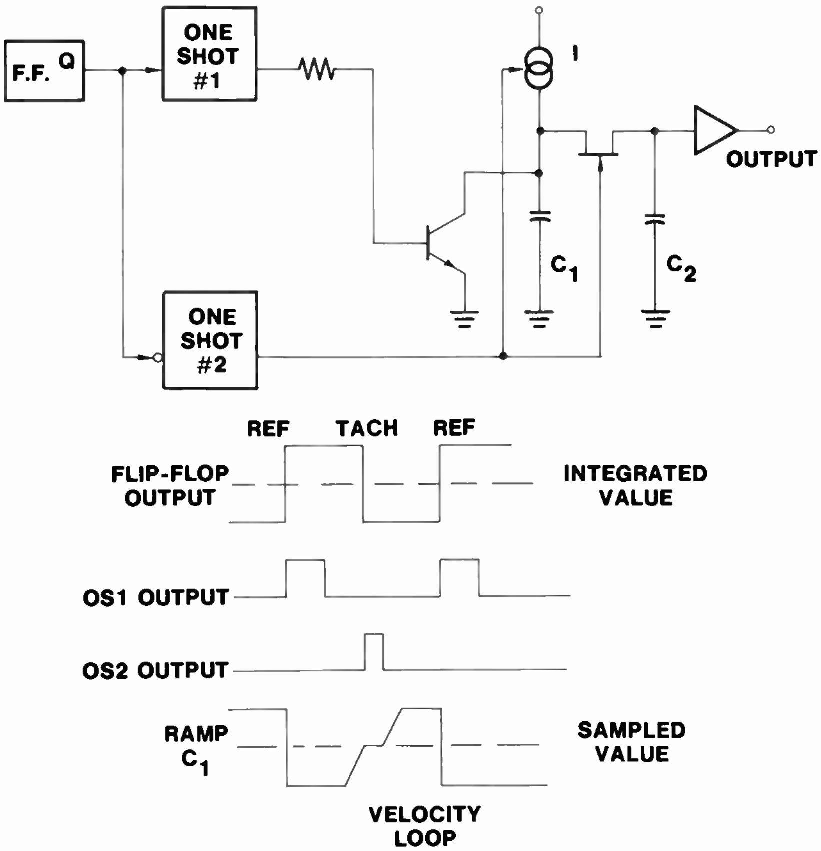


Fig. 117 Removal of Clocking Signals by Clamping

pulse also turns off the current generator during the sample time to further reduce the carrier component. The output signal is proportional to the difference in phase between reference and tachometer signal.

8.6 REEL SERVOS (Oldershaw)

Constant Torque Method The reel motors are the highest power-consuming components of the video tape recorder. An important part of their design is to minimize noise, since the RF signal off tape is in the order of tens of microvolts, whereas the switching spikes on the motors can be tens of volts when changing modes.

The reel motors can operate in either a constant-torque or a constant tension mode. In early machines, constant torque was provided by means of a resistor connected in series with the motor from a voltage source much higher than the motor back-EMF in order to provide a constant current through the motor. The torque provided was Kt x Im where Kt = motor torque constant and Im = motor current.

On a 2-in (5-cm) quad recorder with a 12-in diameter (30-cm) reel, the torque required is 60 to 90 oz inches for 10 to 12 oz of tension. (See Fig. 118.) On a one inch helical recorder the required torque, allowing for frictional plus accelerative torque, is approximately the same.

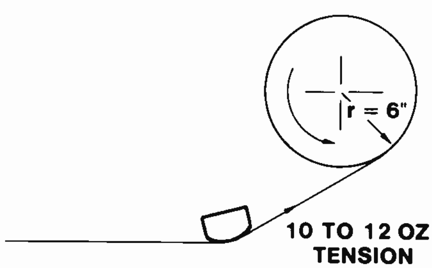


Fig. 118 Torque as a Function of Radius

For fast wind modes, forward or reverse, the capstan pinch roller is disengaged, and the motor currents in the supply and take-up motors are unbalanced, to control the tape direction. This requires switching the large high wattage resistors that are in series with the motors, which has been done with relays or electronic switches. The advantage of this method is that small reel motors are required (less than 150 oz in), and because of the limited available torque, the system is very gentle with tape and makes a uniform tape pack in rewind, an important consideration for long-term or archival storage.

A disadvantage is that this is not a closed-loop servo system and as the pack diameter changes so does the tension across the video head. For example, with a pack diameter change of 3/1 the tension might vary from 6 oz to 18 oz. A further drawback of this simple system is the limited acceleration of the reels due to insufficient torque. This makes the video tape recorder unsuitable for the new automatic editing systems, in which prompt access to each cue point is significant. In addition, the high voltage and high wattage resistors needed do not lend themselves to the new compact helical designs.

Constant Tension Method Long vacuum columns (2 to 3 ft.) to isolate the *read/write* portion of the transport from the supply and take-up reels have been in wide use in the computer industry for many years. This technique first appeared in a video recorder in the Ampex AVR-1, with vacuum columns less than 12" long, and was used subsequently on the cassette video recorder ACR-25 with vacuum columns of 6-in length.

In the *constant tension* method, the tension across the video and audio heads remains constant. It is independent of reel torque and pack size, and requires a closed loop servo that varies the motor torque to maintain the required tension across the video head as the pack size varies. In machines using vacuum columns, the tension is determined by the cross sectional area of the column and the applied vacuum. The columns have ample tape clearance forming a high loss system for the vacuum supply but ensuring that tape slitting errors do not cause sticking. Excellent isolation of reel torque variations from the video head is provided at all speeds and acceleration. A closed loop servo between column sensors and reel motor keeps the tape loop in the center of the column. (See Fig. 119.)

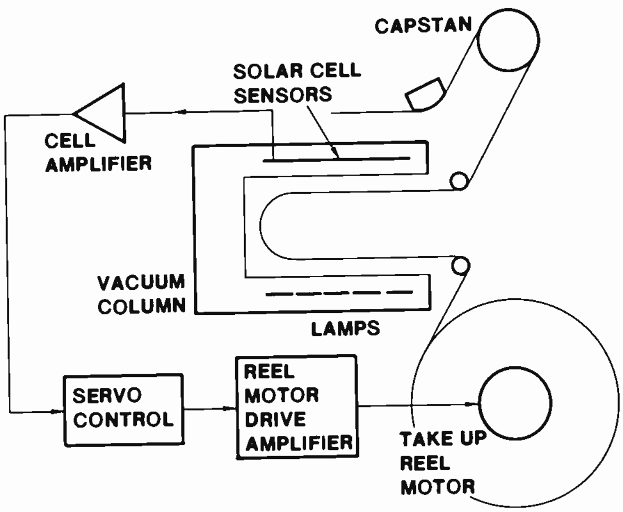


Fig. 119 Closed Loop Servo Using Vacuum Column

All tape motion is controlled by the capstan. As the capstan pulls tape out of the column, more of the photocell sensor strip is exposed to light from the lamps in the opposite wall. The change in cell current is amplified, a correcting signal is sent to the reel drive circuitry to replace tape in the column from the tape reel, and so the tape is kept centered in the column.

Another constant tension method has been developed in recent years which eliminates the need for a large vacuum pump in the machine. Examples are the Ampex AVR-3 and VPR-3. This is the low mass tension arm which rotates through a small arc, usually less than 90°. The tape tension is determined by the spring force on the arm when in the center of its range. Isolation of reel torque from the video head during acceleration is not as good by this method since displacement of the arm causes small changes in the spring force. A closed loop servo between tension arm and reel motor keeps the arm in the center of its range. (See Fig. 120), and all tape motion is controlled by the capstan. The closed loop system operates in the same manner as that of the vacuum columns using a sensor whose output varies with change of tension arm shaft angle.

A variety of sensors has been used for this purpose. One frequently used is the cadmium sulphide photopot in which a voltage is applied across the ends of the pot network and an illuminated slit of light photo-couples a portion of the voltage out, (Fig. 121). As the illuminated slit rotates, the voltage swings from zero to the fully applied voltage. Linearity is good, and thermal drift is insignificant since the output is a ratio of the applied voltage. The response time of the cadmium sulphide element is inclined to be slow.

Other methods used on video tape recorders include a rotating Hall sensor in which a magnet rotates over a Hall effect sensor. Both response time and linearity are good in this method.

A magnetic E core assembly also has been used, excited at 100 kHz. The "E" limbs are wound in opposition and the *I* portion of the transformer is attached to the rotating tension arm. When the arm is in the center of range, the output signal from the center limb of the transformer core has equal coupling from both end limbs, and the signals cancel, but as the *I* portion of the core rotates, the output signal unbalances, and by means of a synchronous detector will rectify to a dc signal proportional to the angular displacement. Response time and drift are good, but linearity is poor over large angular swings.

Reel Motor and Motor Drives In constant-tension systems using a closed loop servo, much larger reel motors are used to provide the accelerative torque. Machines can attain full speed, or return from full speed to *stop,* in 2 sec. The motors found in the more recent recorders have torque ratings of 1000 oz in, and 300 oz in in the one-inch helical Type C recorders. The motors are always dc motors though they may be driven from a rectified ac supply. Linear dc drive amplifiers are unsuitable because of the high power involved. SCR controlled MDAs operating from 60-Hz alternating current have been widely used with the large quad video tape recorders, but more recently switching-type drives have come into use in the smaller 1-in tape recorders. These operate at a chop rate of 25 kHz and use careful filtering and shielding to prevent switching noise from interfering with the audio and video signals. The output signal is also filtered before being applied to the motor. Even though the motor inductance is large enough to integrate the switching waveform, the resulting magnetic field would cause interference in the audio heads.

A diagram of one type of SCR control is shown in Fig. 122. A motor having two field windings is used in a series configuration. The 60 Hz power line is full-wave rectified on each field winding, using SCR's as part of the diode bridge. To produce forward torque, a gate signal is applied to SCR1 and SCR2, and for reverse torque, SCR3 and SCR4 are fired. The gate control logic turns the SCR on during the 60 Hz alternating cycle, and turns off at the next zero crossing. Figure 123 shows typical waveforms as the motor goes from *forward* to *reverse*.

Gate control logic for the SCRs consists of a ramp generator and threshold detector to convert the incoming analog signal to a switched drive signal which controls the angle of firing of the SCR, always turning off at the power line zero crossings. A cosine corrector is also required since the output power would be a function of the sine of the firing angle. This can be seen in Fig. 124, where a small change in angle produces a much bigger change in power at the center of the half cycle than at the zero crossings.

Reel drive MDAs using SCRs are efficient due to the small voltage drop across the active devices, and are compact enough to mount directly on the back of the motor.

8.7 REEL-TO-CAPSTAN COUPLING SERVOS (Clark) Reel-to-capstan coupling servos are used only on machines which use the capstan to move tape from reel to reel in all modes of operation, including high speed shuttle. Machines which do not use the capstan for moving tape in shuttle modes do not need a coupling servo, because there is sufficient tape storage in the compliance arm systems to absorb the acceleration transient from stop to play or record speed. In shuttle mode on these machines the tape is accelerated by the reel motors themselves, so the acceleration can never exceed the capabilities of the reel motors.

On a recorder which uses the capstan for shuttling tape, however, high rates of acceleration may be experienced for periods up to several seconds. If the acceleration produced by the capstan is greater than the rate at which the take-up reel motor can accelerate, a loop of loose tape will be thrown, resulting in probable damage to it. It is therefore necessary to limit the capstan acceleration to a rate not greater than the reel acceleration capability in shuttle modes.

The reel-to-capstan coupling servo limits the capstan acceleration only when a tape storage sensor indicates that it is near the limit of its range due to excessive tape acceleration. In this case, a correction signal proportional to the excess displacement is subtracted from the capstan speed command, correcting the capstan speed reference signal downward to a value such that the capstan acceleration does not exceed the acceleration capabilities of the reels. The bandwidth and compensation of this feedback loop must be carefully chosen to coordinate with the capstan speed loop and the reel servo loops, because the loops are effectively in tandem and will all interact. The coupling servo loop will normally have a response intermediate between that of the reel servos and the capstan speed control servo. See Fig. 125.

8.8 AUTOMATIC TRACKING

AUTOTRACKING FOR QUADRUPLEX RECORDERS (Oldershaw)

Background Autotracking servos are used on two-inch quad recorders to keep the video head tips fully registered on the recorded video tracks without the need to manually adjust the tracking control. Manual operation is still retained for editing, and can be selected by means of an *auto/manual* switch.

As video is recorded by the headwheel, the control track is recorded by a stationary head placed 0.725 in (1.84 cm) ahead of the video tips, the exact position being determined by means of a factory-made standard alignment tape. Since the video tracks can be only 0.005 in (0.0127 cm) wide, an error of 0.0025 in (0.0063 cm)

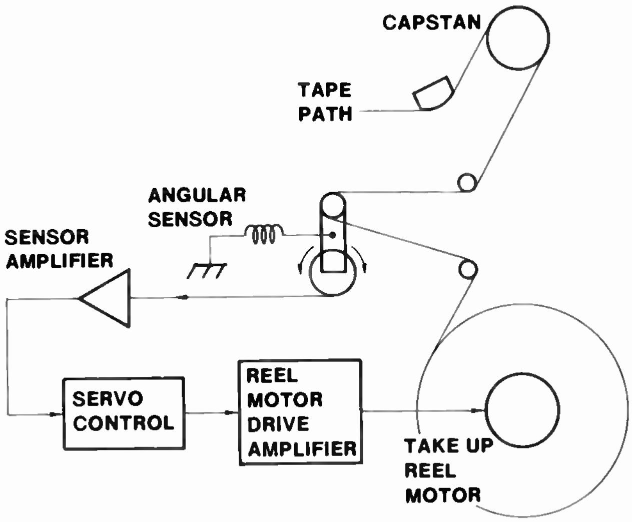


Fig. 120 Closed Loop Servo Using Tension Arm

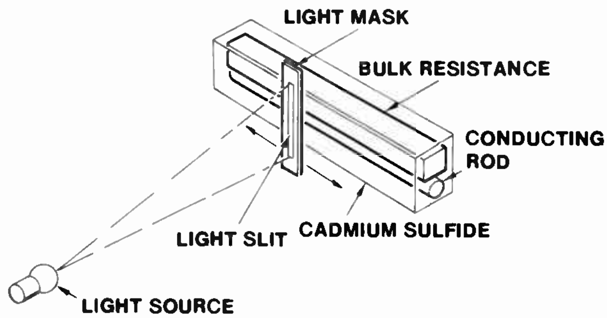


Fig. 121 Cadmium Sulphide Photo Pot Sensor

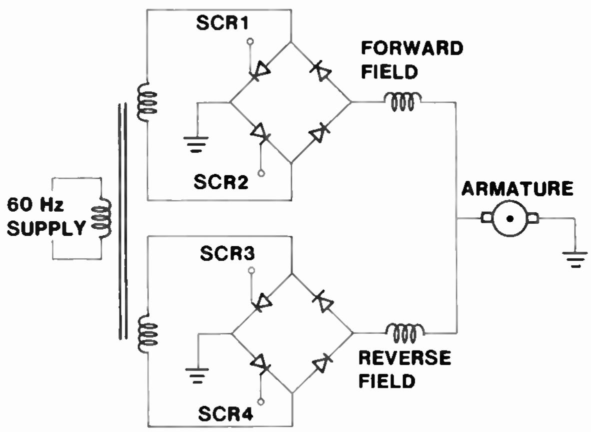


Fig. 122 SCR Controlled Reel Motor

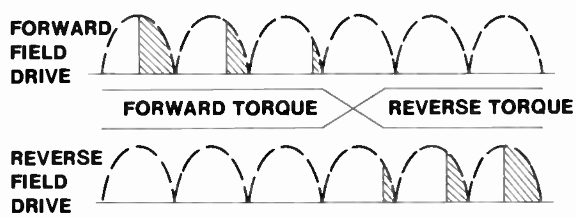


Fig. 123 SCR Controlled Reel Motor Waveforms

will produce a 6 dB loss of RF, and also will result in an interference pattern on the playback picture due to interference from the adjacent track.

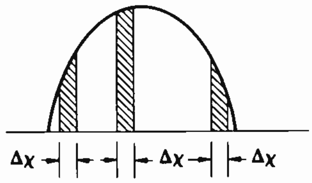


Fig. 124 Power as Function of Firing Angle

Autotracking was first introduced on the Ampex VR1200, when it was felt that with the increasing use of the editing equipment, it was important to have a video tape recorder which needed no manual adjustment while operating. When the cassette recorder ACR-25 was introduced, capable of playing 10 second spot commercials back-to-back, it was no longer possible to preview each tape and set tracking phase, and an autotracking method became mandatory.

Method When tracking manually, it is necessary to adjust the tracking control to obtain maximum RF, as indicated on an oscilloscope or meter. It is normal practice to trim either side of the peak reading a few times to establish the highest value. This is also true of the autotracking method. A low frequency sinusoidal *dither* signal is injected into the capstan MDA along with the closed loop error so that the video track on tape is mis-tracked from side to side across the video head to determine where the peak value lies. An RF-envelope detector provides the signal level resulting from the injected dither signal, and a synchronous detector using these two signals provides an off-track error signal which is coupled back into the loop to correct the capstan phase.

A system block diagram is shown in Fig. 126. When the *manual/auto* switch is in the *manual* position, the manual control changes the phase of the delay between the headwheel tachometer and control-track phase comparator in the normal way to move the relative phase of the recorded video tracks with respect to the playback tips on the headwheel. When the switch is set to *auto* the tracking delay obtains an input signal from the autotracking error.

An oscillator is chosen for the dither signal which is below the audio passband and is injected at a level which does not significantly add to the audio flutter. Nevertheless, it is a flutter component, since the audio is on a longitudinal track and the dither produces a longitudinal displacement. The oscillator is free running, not locked to headwheel, and so does not arithmetically add to flutter on multigeneration audio. The RF on tape is envelope-detected in the signal system, and the level controlled by an AGC having a time constant longer than the 10 Hz dither.

The detected RF is passed through a 10 Hz-bandpass filter to extract the dither components, and is applied to a synchronous detector which produces an output signal proportional to the off-track error. Figure 127 shows the operation of the synchronous detector. When the dither signal is superimposed on the RF envelope, the return signal has a different phase on each side of the track center. At the middle of the track, a lower amplitude, twice-frequency component is produced. On the left hand side of track center in the diagram the return signal is in opposite phase to the inserted dither. On the right hand side of track center the return signal is in phase.

The square-wave 10-Hz signal used as an input to the synchronous detector is in phase with the dither component, and is used to rectify the return signal from the 10 Hz-filter. The rectified error is shown in the diagram as having a negative value on the left-hand side of track center and a positive value on the right-hand side. A long integration time, in excess of 1 sec, is used to distinguish the low-level wanted signal from other low frequency transport-flutter components.

Lock-up on Non-Standard Tapes When the play button is pressed, the autotracking is inhibited and the tracking delay held to its center value, presuming the tape to have a standard control track format. The frame pulse on the control track signal is first matched to the reference frame pulse, and the 240-Hz control track is then locked to the headwheel tachometer using the control track phase comparator. Once the error

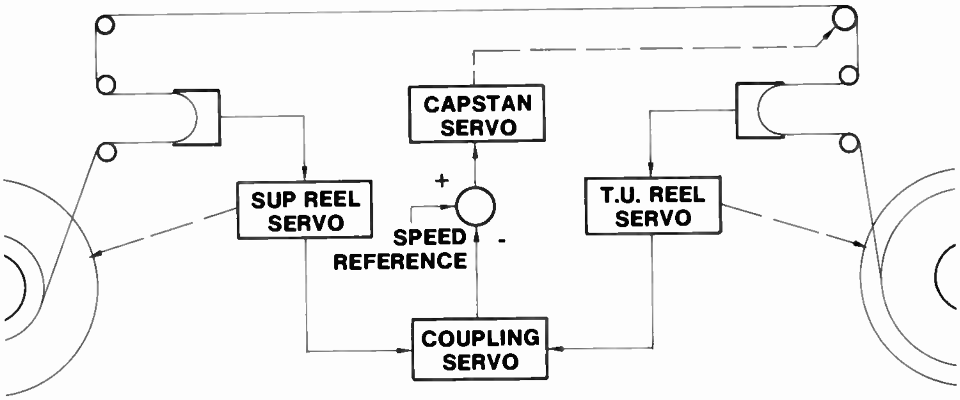


Fig. 125 Reel-to-Capstan Coupling Servo

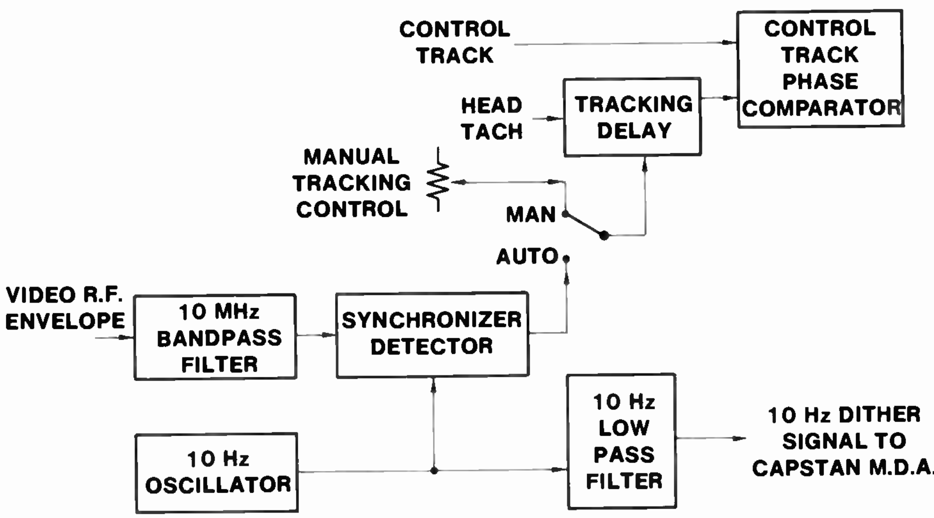


Fig. 126 Block Diagram of Autotracking System

signal has settled, the autotracking is *enabled* and peak tracking is obtained.

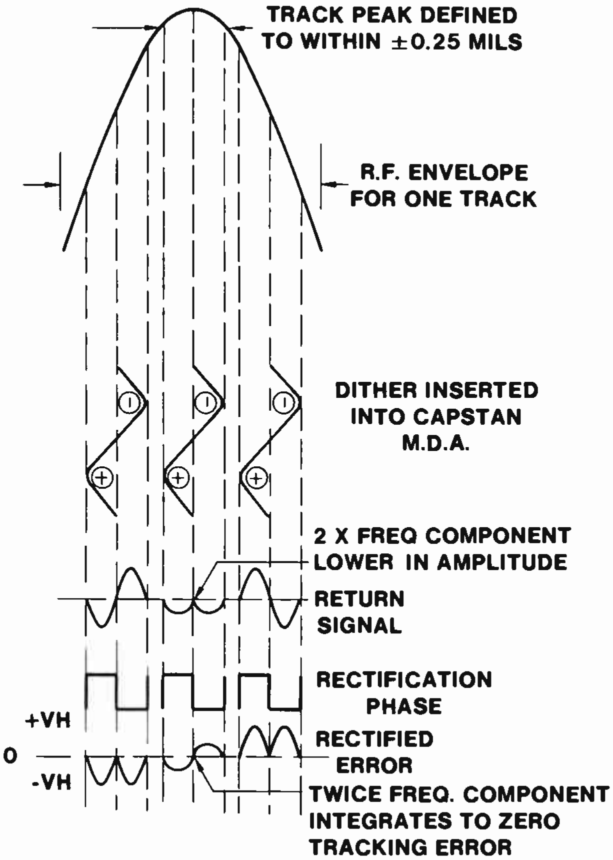


Fig. 127 Operation of Synchronous Detector

If the control track is non-standard and has a displacement greater than one half track width, then it is possible during the peaking operation to be on the center of an adjacent track. When this happens, the off-tape vertical TV signal is one msec out of phase with the reference vertical information. A separate detector referred to as the *track selector* examines the signals for this condition. It uses reference and off-tape vertical information to determine whether the correct track has been selected within a window of tolerance. If the off-tape vertical lies outside the window, an overriding bias is applied to the servo as an error signal, with sufficient amplitude to move the tape to the next track.

On some two-inch quad video tape recorders an additional feature was added by which a tape could be played back even if it had no control track at all. Alternatively, the control track could be rewritten if the control track format showed an excessive error. This was done by means of the *auto-tracking* circuits. Lock-up under these conditions was much longer than usual but it was a means of saving a tape that had been incorrectly recorded. If the *control track presence detector* showed an absence of control track, then no effort was made to use the control track frame pulse in the framing cycle of lock-up. Instead, a frame pulse from demodulated video was decoded and compared to reference. Unlike the frame pulse on the longitudinal control track, the demodulated pulses are disturbed as the video head crosses tracks, but it is a converging process and after a second or two the video tips settle on the correct track. Under these conditions, the autotracking error signal is substituted for the control track phase comparator error signal rather than just modulating the delay to the control track phase comparator, and the time constant of the autotracking detector extended to several seconds. It takes approximately five seconds for the servos to settle for a satisfactory playback, but many valuable tapes have been recovered by this means.

8.9 AUTOMATIC SCAN TRACKING (AST) FOR C-FORMAT MACHINES (Ravizza)

Requirements for Special Effects To obtain special-effects reproduction such as slow and still motion, a VTR must transport tape at a different speed from that at which it was recorded. More particularly, if a field per scan format VTR is in the stop motion mode, the video head must continuously scan the same recorded track. The resulting geometric error between the stationary recorded track and the reproduce head scan is shown in Fig. 128.

Uninterrupted video reproduction under these conditions requires the aid of a head tracking servo that will deflect the playback video head in a direction perpendicular to the recorded track to prevent undesirable mistracking, as shown in Fig. 128. Here the tracking servo must deflect the reproduce head with a saw-tooth waveform at the scanning frequency. In addition, as the track angle varies due to continuing changes of playback tape speed for various slow motion rates, the tracking system must continuously respond to these changes by generating a complex sawtooth waveform, as shown in Fig. 129. A basic block diagram of a head tracking servo is shown in Fig. 130. Head-tracking errors are determined by detecting variations in the amplitude of the playback RF envelope. Any tracking variations are detected, amplified, and processed, to be used for repositioning the reproduce head to track center.

A head deflection range of about 0.011 in (0.325 mm) is required to track a reproduce speed range from -1X normal to +3X normal on the 625 line Type C helical scan format. This deflection is most commonly achieved by mounting the head transducer on the free end of a thin cantilever beam made of bimorph material, as shown in Fig. 131.

A bimorph consists of two thin strips of piezo-ceramic material bonded together. With applied voltage, one portion expands and the other contracts. By anchoring the base of the beam, an effective deflection of the tip can be obtained.

Piezoceramic material has no piezoelectric properties when first fabricated, because the electric dipoles of the granular particles are randomly oriented. The material must be polarized to align the dipoles in a *poling* operation. A deflector drive voltage of about ±200V is necessary to cover the required range.

Desirable characteristics of a bender-element configuration include low mass, fast response, and rigidity in directions other than the intended direction of deflection.

Another characteristic of the deflector drive is that voltages applied with a polarity opposite to the original polarization direction of the bimorph crystal must be limited to a low level or not applied at all. Figure 132 shows a method of drive using two bias voltages to prevent depolarization. The arrows show the direction of original polarization with the arrow pointing from plus to minus. If the bias voltage V_{Bi} equal to the peak value of the drive V_D, an opposite polarity drive cannot be applied to the deflector. An alternate method is shown in Fig. 133. This configuration limits the amplitude of the depoling drive through the use of zener diodes.

At the extreme ranges of deflection, the reproduce head would have a zenith error of about one degree, as shown in Fig. 134. This angle reduces optimum head-to-tape contact, and is significant because of the short wavelength of the video recording (<100 μ"). This loss can be effectively reduced by any of several ways, as shown in Figs. 135 and 136.

One approach is to recurve the bimorph bender beam by cross-wiring the deflector plates at a point about one-third from the free end. The net effect is that by inverting the drive polarity to the end plates, the end segment of the beam is deflected in an opposing direction to reduce the zenith angle as shown in Fig. 135. Another implementation is to use multiple bimorphs spaced from each other at the mount and at the tip by a hinged bridge. Figure 136 shows that this configuration keeps the hinge connecting the two blades parallel to the tape. As the video head tip is mounted perpendicular to the hinge, it also will remain perpendicular to the tape at all deflection positions. Since the deflector is in a cantilever configuration, it exhibits a natural mechanical resonant frequency. Depending on the particulars of the construction, the resonance may be at or near lower order harmonics of the deflector sawtooth drive. Under these conditions the deflector must be damped to eliminate spurious mechanical vibrations.

By taking advantage of the fact that the piezoelectric effect is bi-directional, a small portion of the deflector is isolated and used in the generator mode for damping feedback. Any spurious vibrations of the head are picked up by the sense strip and fed back into the deflector driver input 180° out of phase for cancellation.

Other systems damp the resonance vibrations by proper placement of *dead rubber* between the moving blade and its stationary holder. The net bandwidth of such a driver and damping system is about 1 KHz.

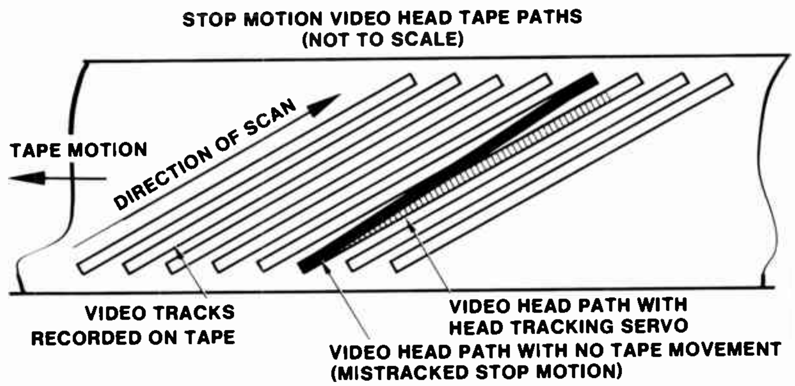


Fig. 128 Head Tracking Geometry

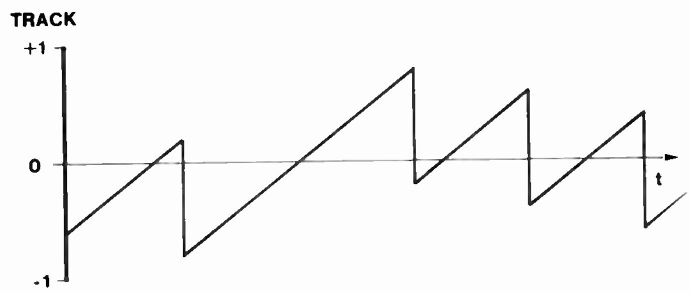


Fig. 129 Head Reflection Waveform for 1/5 Speed Slow-mo

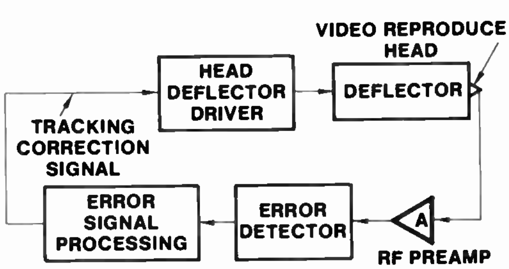


Fig. 130 Head Tracking Servo

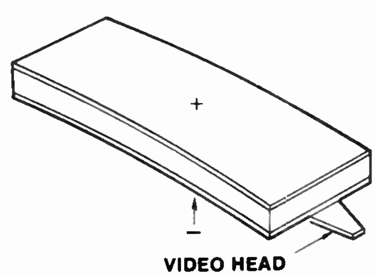


Fig. 131 Bimorph Strip and Head

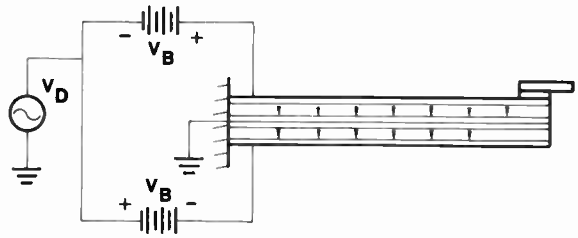


Fig. 132 Deflector Drive Using Bias Offsets

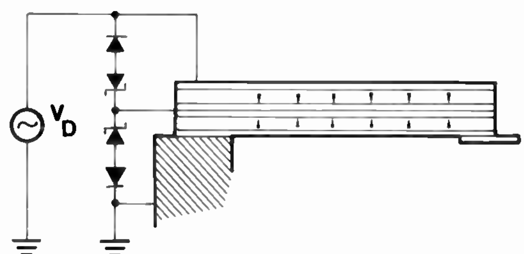


Fig. 133 Deflector Drive Using Zener Diodes

Tracking Error Detection If the detected RF envelope from the reproduce video head were used as a tracking error signal, a decrease in the RF level would allow the servo to sense when mistracking was occurring. However, the servo would not be able to determine in which direction it should react to correct the error.

The method that is used in head tracking servoes to obtain both error amplitude and directional information is *dithering.* This involves intentionally introducing an error, or dither, signal by deflecting the reproduce head a small amount in each direction from track center in a sinusoidal manner in order to create a carrier amplitude modulation of a known frequency and phase. The RF signal is then passed through an envelope detector, followed by a synchronous detector, as shown in Fig. 137. The reference for the synchronous detector, in phase with the RF dither signal, is a square wave, usually derived from a system clock or the head deflector sensor.

When the head is centered on track the envelope modulation due to dither contains only twice dither frequency components. Therefore, when this signal is synchronously detected at the dither rate there is no output, as shown in the center of Fig. 137. When the reproduce head is off track center, the RF envelope will now exhibit a dither frequency component, which is synchronously detected into a dc value. If the head is off track in the opposite direction, the fundamental component will be 180° out of phase from the previous condition. This will result in a negative dc output from the synchronous detector. The dither frequency is typically in the 500 Hz region.

An alternate method of determining tracking error is to use a computer-controlled hunting system where a known change in deflector position is made, followed by a sampling of the resultant change in RF level. Based on the results of the sample after the change, the computerized algorithm will eventually seek optimum tracking.

Since the recorded video information frequency-modulates an RF carrier, any RF amplitude change due to tracking dither can be eliminated in the limiter circuits of the demodulator. Conversely, care must be taken to ensure that any spurious AM components of the RF carrier due to video information do not reach the tracking detector. This can be accomplished either by sampling the RF envelope only during horizontal sync time (since picture content does not affect sync amplitude) or by feeding the envelope detector at the output of the RF equalizer but before the *straight line network.* This is the point in the play-back chain at which the amplitude vs frequency response is the flatest, ie., the point at which the least amount of amplitude modulation is found on the FM envelope. Long term variations of RF level are accommodated by an AGC Circuit.

Error-Signal Processing The major function of the error-signal processing circuit is to generate the complex sawtooth waveform that represents the geometric correction necessary to keep the reproduce video head on track when reproducing at other than normal speed.

Figure 138 shows the required head deflection waveform used to drive the movable head in the still mode. In this mode,

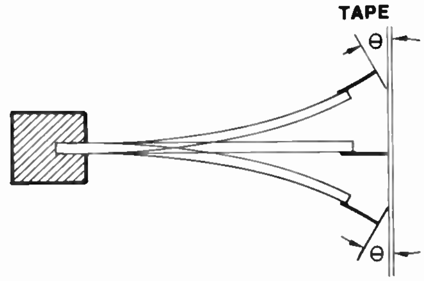


Fig. 134 Head to Tape Angle as a Result of Deflection

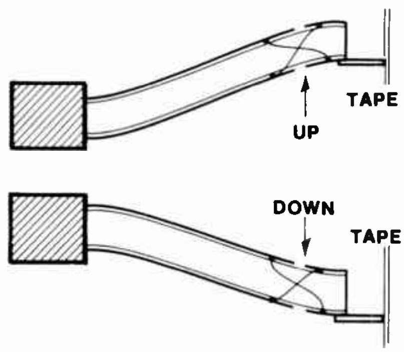


Fig. 135 Zenith Error Correction by Deflector Re-curving

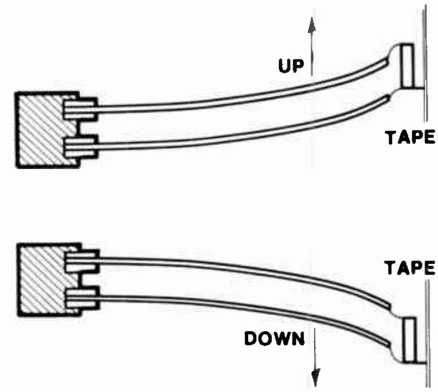


Fig. 136 Zenith Error Correction by Multiple Deflector Hinging

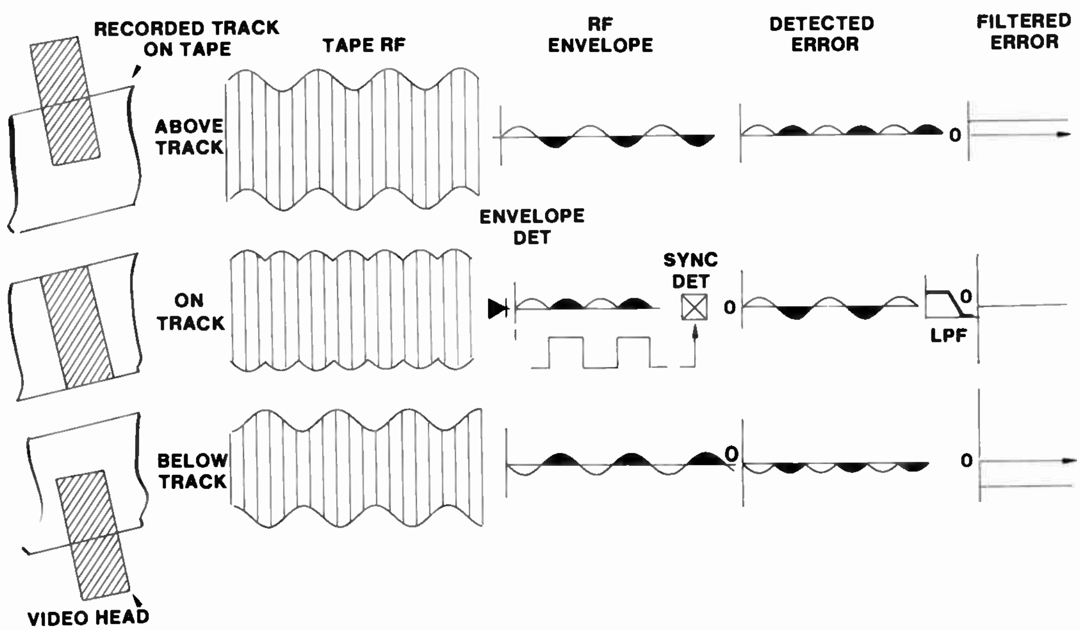


Fig. 137 Synchronous Detection of Tracking Error

the video head repeatedly scans the same track, which in the Type C field-per-scan format means the same TV field is being played back repeatedly. As shown in Fig. 138, when the video head scan reaches the end of a track, the head position must be reset to its initial value to begin scanning the same field again. Advantage is taken of the format dropout time, in which no video information is recorded for about 10 lines during vertical blanking, to reset the head deflector back to its initial position. The bandwidth of the driver/deflector system is sufficient to move the head within the 0.5-ms dropout time.

If the tape is transported slowly in the forward direction, the dc level of the deflection waveform will move down, or in the negative direction. The head tracking servo cannot remain locked to the same field indefinitely as the tape is moved forward. What must occur is for the servo to abandon tracking the current field and lock onto the next adjacent one. This field-changing or track-changing sequence is started by simply inhibiting one of the resets in the sawtooth waveform, which allows the video head to scan onto the next track as shown in Fig. 139. The decision to inhibit a reset pulse is based on the instantaneous value of the waveform at the end of the scan. Here, the logic circuitry determines that if the waveform is less than zero deflection, i.e., negative, the next reset is inhibited.

Fig. 140 shows the reset control when the tape is moved in the reverse direction. The dc levels of the sawtooth waveform moves in the positive direction. Again, the servo logic must decide when to jump from field 2 to field 1. This is accompanied by determining when the instantaneous deflection at the end of scan is greater than a level of one track in the positive direction. When this occurs, a two-track negative reset command is generated.

A block diagram of one configuration of an error-processing circuit is shown in Fig. 141. The output of the tracking error detector feeds the input of an operational amplifier in an integrator configuration. This allows the closed-loop tracking servo to control both the slope and the dc level of the correction waveform. A *reset* command is implemented by sampling the level of the integrator output at the end of the scan, using a scanner tachometer for basic timing, and deciding whether or not to generate reset pulses by triggering the track jump pulse generator.

To maintain the head deflection waveform favorably centered about the zero deflection point, the reset decision levels as shown in Figs. 139 and 140 must be controlled by tape speed. This is accomplished by measuring the period of a tape-driven tachometer that can then be used to vary the reset levels, depending on tape speed.

The dynamic correction processing circuit provides servo gain at the scanner rotational rate and its harmonics. Since the helical Type C format recorded track is over 16 in (40 cm) long, small nonlinear tracking errors can occur. These errors will have a fundamental frequency at the scan rate, since the error pattern repeats with each head rotation. With the dynamic correction servo gain optimized at these frequencies, any residual tracking error can be corrected by the servo.

Tracking-correction output to the tracking head deflection driver consists of a summation of the integrator output for variable-speed tracking, dynamic correction output for non-linear errors, and a low- level dither signal for error-direction sensing.

Vertical-Sync Playback Processing

Whenever the tracking video head jumps, either to repeat or to skip the next field, there is a predictable timing discontinuity in the reproduced video. The magnitude of the interruption is due purely to the recorded format, and related to the incremental horizontal line skew between recorded tracks. With the Type C format, for 525 and 625-line television systems the horizontal timing shift between two adjacent tracks (fields) is 260 and 309 lines respectively. Another aspect of the Type C format which must be considered is that vertical sync for a particular field is recorded after the approximately ten-line drop-out. The net result of these factors is that a track jump during the drop-out produces a timing shift between reproduced vertical sync and video of the following field. In 525 line systems a shift of 2.5H is produced, whereas

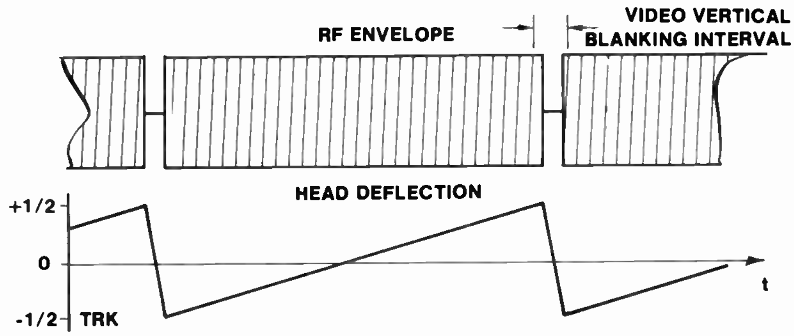


Fig. 138 Playback Envelope in Still Field Mode

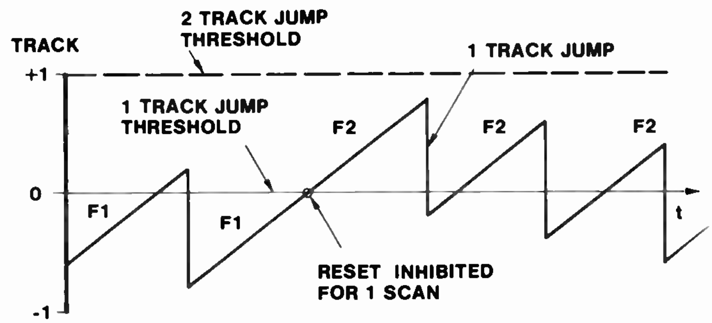


Fig. 139 Error Processing Output for 1/5 Speed Forward Mode

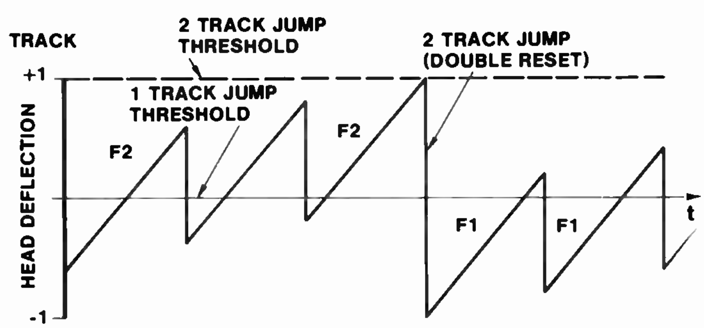


Fig. 140 Error Processing Output for 1/5 Speed Reverse Mode

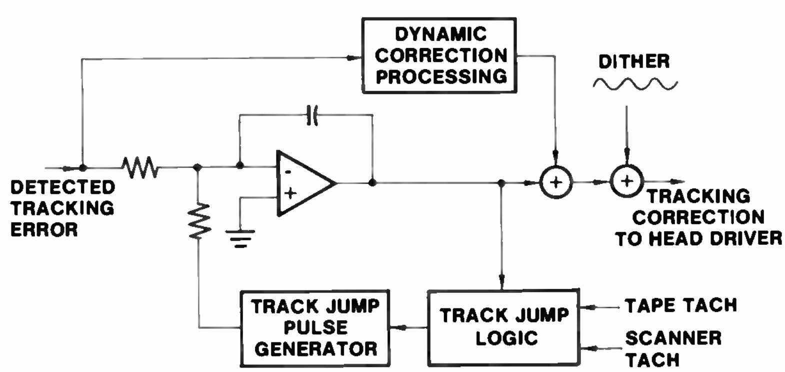


Fig. 141 Error Signal Processing Based on Head Deflection I Information

in 625-line systems the shift is 3.5H. Also, the polarity of the phase shift depends on the direction of the track jump. Finally, under some reproduce conditions, there may not be any serrated vertical-sync pulses in the video output, which means that vertical sync cannot be detected by a conventional integrating circuit.

For the foregoing reasons, a vertical-sync signal must be generated that does not depend on the presence of serrated pulses, and can be programmed to change by increments of 2.5H or 3.5H if the tracking servo system either steps or slips a track, depending on whether the playback mode is faster or slower than normal.

A timing diagram of the processed vertical-sync signal output for various reproduce conditions for the 525 line format is shown in Fig. 142. In Fig. 142a the normal reproduce condition is shown where the vertical-sync drop-out begins after the second serrated pulse, and the regenerated and processed vertical sync is in time with playback vertical sync. Fig. 142b shows the *still* playback condition with the tape unfavorably parked to the extent that all vertical broad pulses are missing. Since the playback head is repeating a field by stepping back at the end of the scan, the processed sync output must be advanced from playback sync by 2.5H as shown, in order to be valid for the following field which begins after the vertical sync dropout. An opposite condition is shown in Fig. 142c, where the tape is moving at twice normal speed. Here the tracking head must step forward at the end of a scan in order to skip every other field. Processed vertical must therefore be delayed in order to be in time with the following video.

Figure 143 is a simplified block diagram of a processed vertical-sync generator. Input is taken from two sources, stripped sync from *demodulator-out,* and the tracking-servo jump command. A horizontal phase-locked loop generates a tape synchronous 2H frequency. This is used as a clock input to a field counter, that can store 525 (or 625) 2H pulses per field.

As noted earlier, vertical sync may not always be present. Therefore, the first two equalizing pulses in the vertical-blanking interval are used as a signal to trigger the generation of a complete vertical-sync-interval signal. Since equalizer pulses are shorter in time duration than serrated vertical pulses, care is taken to insure a safe margin of noise immunity. For this purpose, a *noise-immunity gate* circuit precedes the pulse detector circuit that is used to load the pre-settable field counter via the reset logic circuit. This is another noise protection circuit that only allows an off-tape load to reach the counter if there are eight consecutive timing disagreements when compared to the *self-load pulse*. The intention is to provide immunity against random single or multiple tape errors, yet reasonable rephasing time (eight fields) for initial synchronization.

Depending on track jump data, the counter is preset for a normal 525/625 count (no track jump) or modified in increments of ±5 2H pulses (or ± 7 2H pulses in 625 line systems), as dictated by the tracking servo commands. This insures that the counter will be in the same state at the second equalizing pulse in every field.

The counter output logic, which is also driven by jump commands, controls time shifting of the processed vertical-output signal, based on jump data.

8.10 MICROPROCESSOR CONTROLLED SERVOS (Oldershaw)

System Configuration A significant new tool for use in videotape recorder servos was the microprocessor. It is used in many ways and has resulted in a considerable reduction in size and cost. It provides bus compatibility with all other systems within the video tape recorder, and thereby reduces harness complexity. Field changes can often be made with only a change of program (EPROM), and as improvements in diagnostics are made, a customer can subscribe to the updates to improve his system, all without the use of a soldering iron.

There is no doubt that system design will go even further in the future, but in 1982 a one inch Ampex VPR80 Type C video tape recorder was introduced in which the entire servo electronics was contained on one board with many self-checking features never possible before

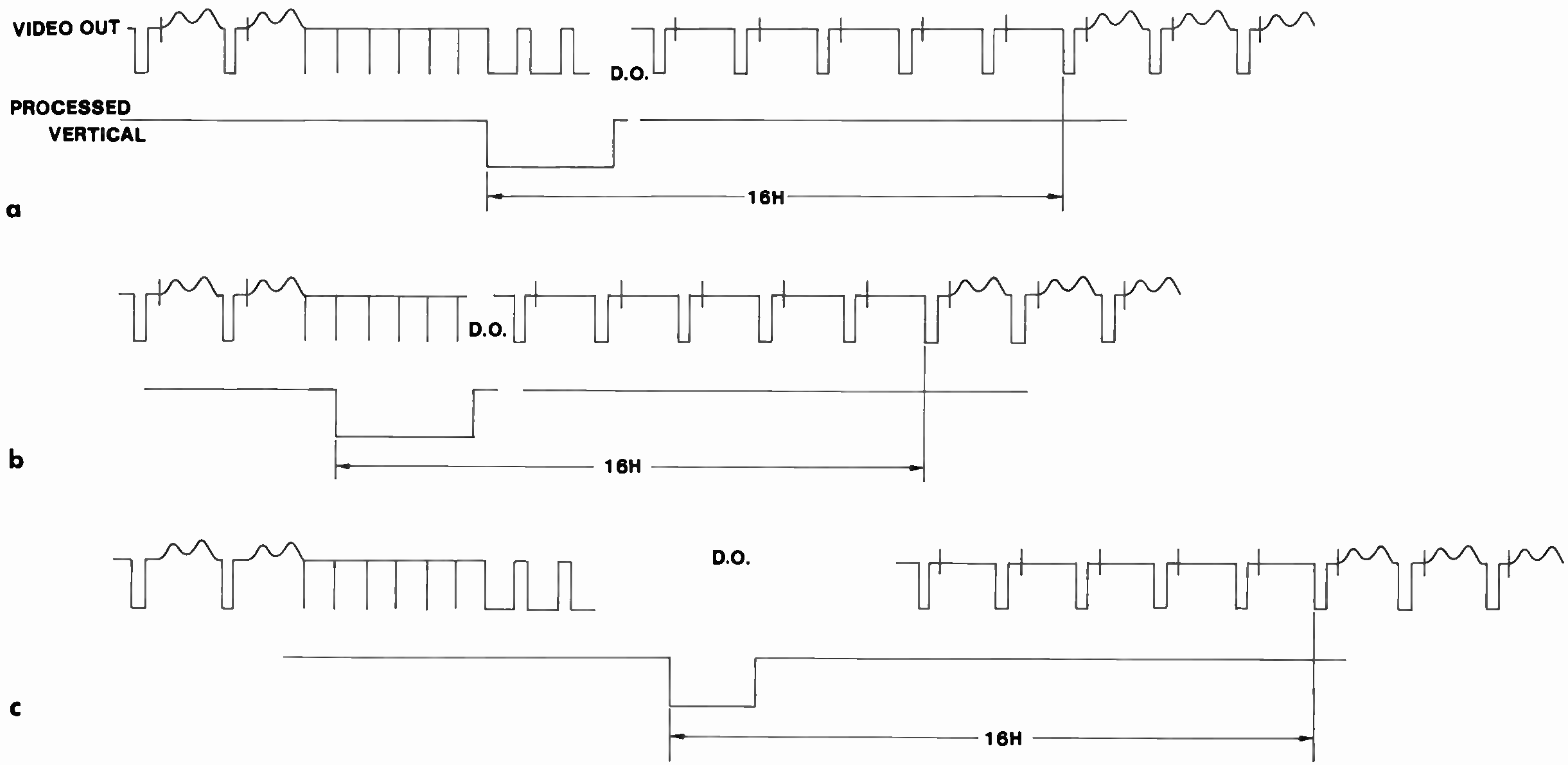


Fig. 142 Processed Vertical Output for Various Playback Conditions - 525 Line Format

because of the volume of hardware that would have been required.

The capstan servo has been chosen as the one for which to describe the application of microprocessors, since it has more variations than the reel or scanner servos. In Section 8.5 it was shown how the digital capstan servo replaced the analog servo and the resulting block diagram (Fig. 115 shows a tachometer-lock loop in which the capstan tachometer is locked in phase and frequency to a capstan reference clock. Changing the capstan clock produces a corresponding change in capstan speed or phase, as desired.

In the microprocessor controlled servo, the microprocessor is used with a bus-compatible 16 bit timer IC to provide the reference to the tachometer-lock loop. The timer chip is loaded with a constant from the processor, runs to its maximum count, and reloads, forming a continuous output frequency. To change the frequency, a new load number is presented to the timer IC on the data bus. Each timer IC contains three or more 16 bit counters, that are used to replace one shot and ramp-generator delays as well as clock sources. The source for the timer IC is the crystal controlled 4 MHz clock for the processor.

Two data buses are used, one to communicate with the control system in the machine, and the other an internal data bus with which the processor can communicate with its internal devices, such as RAM, EPROM, timer devices, and internal and external eight-bit ports. Each port or device has its own unique address, and to communicate with a particular device, an address is decoded and used as an *enable* during that particular portion of machine code.

Figure 144 shows the basic configuration. The erasable prom (EPROM) stores the program. A typical size for this is 16k-bytes. No more than one kilobyte of RAM is required. The few analog signals that exist are fed via an analog multiplexer to an A/D converter, the values of which are routinely sampled and stored as a digital word in RAM locations to be accessed at the appropriate program step.

Scanner-tachometer and control track signals are fed to timer ICs to generate the necessary timing delays. The processor runs through the program in a sequential manner and returns and repeats the steps over and over, but many branch decisions are encountered and the time to complete the loop will vary depending on the branch taken. For this reason, the processor cannot be used to make precision timing measurements. The method used to compare the phase difference between scanner tachometer and control track, for example, is to start a timer using the signal edge of the scanner tachometer and stop the timer using the signal edge of control track, giving a time difference as a number of 4-MHz clock cycles. When the phase difference is needed by the program, the 16-bit number is loaded into the processor in two bytes and the counter is reset, ready to make the measurement again. It is arranged that the cycle time of the program does not exceed one field, or one scanner rotation, so that the next measurement will not be missed.

System commands and status are passed over a system bus using any of the available handshaking protocols.

Arithmetic Processing and Filtering It is desirable when going from zero to full speed in shuttle mode to have constant acceleration. This requires the reference clock to the capstan to be stepped in equal frequency increments. The capstan reference clock comes from a timer IC that free runs by counting the maximal count and reloading. For a 16-bit counter the maximal count M is given by:

$$M = 2^{16} - 1$$
$$= 65{,}535$$

The scheme is shown in Fig. 145 with a 4 MHz clock

$$F_{out} = \frac{1}{COUNTER\ PERIOD}$$
$$= \frac{1}{\left[\dfrac{65535 - LOAD}{4\times10^6}\right]}$$
$$LOAD = 65535 - \frac{4\times10^6}{F_{out}}$$

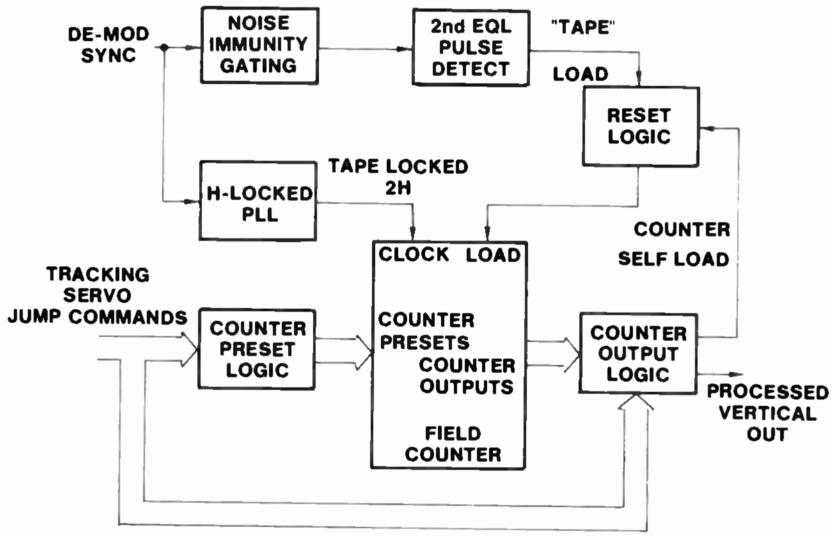


Fig. 143 Processed Vertical Generator

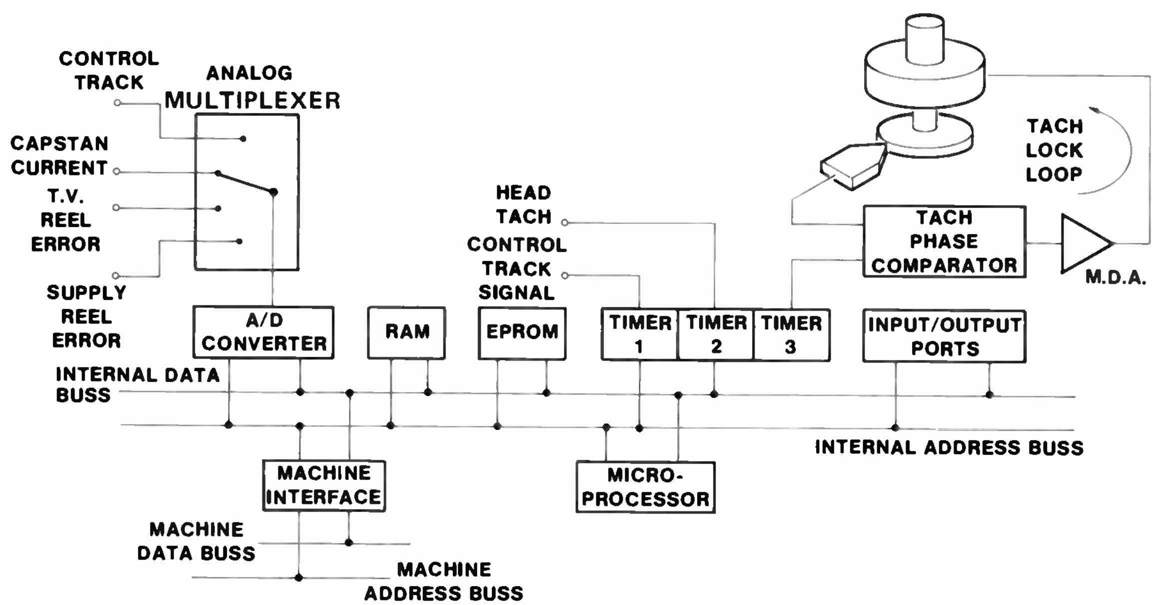


Fig. 144 Basic Configuration of Microprocessor - Controlled Servo Control System

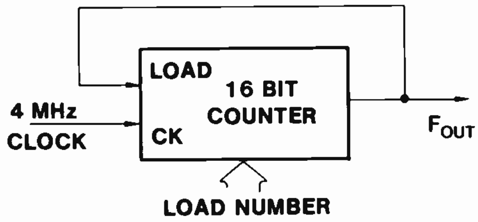


Fig. 145 Counter Loading Method

To change the reference clock in equal increments requires solving this simple equation, but the equation involves dividing by the variable F_{out}. This is a slow operation in the processor and would seriously affect cycle time. A table is set up in program memory to handle this case. The counter load numbers are calculated during the servo design, for example 256 steps from zero to full speed, and the corresponding load numbers are stored sequentially in a table. In stepping through the table, the load numbers are accessed to provide a close approximation to linear acceleration.

Some calculations are done in the processor, and a good example of this is filtering. In the analog domain the average value of a signal is obtained by means of a low pass filter whose *corner frequency* determines the averaging time. In the processor, the same averaging can be achieved by sampling the signal and dividing by the number of samples. The averaging time is the product of the sample period and the number of samples. To make the arithmetic run fast, it is usual to arrange for a binary division so that a series of *arithmetic shift right* instructions is all that is needed.

To understand this, take an example of 21 to be divided by 2 or 4. The number 21 in binary is 10101 as shown in the table, Fig. 146. An arithmetic *shift right* command yields 1010, or 10, which is 21/2 to within the least significant bit.

A second *shift right* yields 101 or 5, so with two *shift right* commands we have very quickly divided by 4. Similarly a *shift left* instruction will multiply the number by 2. Low pass filters can average over numbers of samples other than binary by means of simple algorithms using a *shift and add* technique. An average of about seven samples can be obtained using five *shifts* and one *add* instruction from the algorithm:

$$1/8 + 1/64 = 9/64 \approx 1/7.11$$

If, however, it is wished to divide by π then a full mathematical algorithm is required that is well within the capability of the processor, but prohibitively slow.

2^N	128	64	32	16	8	4	2	1
21	0	0	0	1	0	1	0	1
SHIFT RIGHT								
10	0	0	0	0	1	0	1	0
SHIFT RIGHT								
5	0	0	0	0	0	1	0	1

Fig. 146 Arithmetic Shift Right Operation

A running average is frequently used in servo filtering using the microprocessor in which samples S1 and S2 are added together and divided by two to form an average. The new sample S3 is added to the current average and the sum again divided by 2, which provides a phase advance to the long term average, since the last sample has a weighting factor equal to that of all previous samples.

Wide Dynamic-Range Phase Comparator
The digital phase comparator described in Section 8.7 and used to tachometer- lock the capstan motor, has a dynamic range of only one-half cycle of the high-resolution tachometer. If the reference frequency to this loop is changed abruptly the loop will unlock, relock, and slip several tachometer lines in phase. On videotape recorders using microprocessors, the phase slip is overcome by the method shown in Fig. 147.

A four-bit counter is preset to its mid-range when the capstan is at rest. As the reference clocks the counter up, the output of the D/A converter applies a signal to the motor, and the motor rotates. The capstan tachometer clocks the counter back down to its mid-range position as a steady state speed is reached. During acceleration the counter may lag slightly but does not lose the count. Abrupt changes that unbalance the counter or D/A converter will slowly be clocked out by the capstan tachometer without slipping in phase unless the step change exceeds the counter range. Eight bit counters and D/A converters have been used, giving a dynamic range of ± 64 clock cycles before losing lock.

Measuring Parameters Measuring tape pack diameter in the video tape recorder is done on many models to determine the impending end of tape. In this way the video tape recorder can come to a stop without the tail end of the tape passing across the scanner tips at high speed. The method is to count the number of capstan tachometer pulses that occur for one cycle of reel tachometer and from this the tape pack diameter can be determined. It is usual to average three or four measurements to be sure of the result.

Under microprocessor control, this measurement can be extended from one single dimension to as many as desired throughout the reel pack and can be used to determine the change in reel torque required to keep the tension constant across the scanner. It can also be used to modify the reel servo gain, which is set low upon threading the transport, and modified once a pack diameter has been established.

Waveform Generation Segments of programs are set aside for test waveforms and can be used, for example, to verify the performance of the automatic scan tracking servo (AST) or for setup when replacing an AST video head. The method of waveform generation is to store the coordinates of the waveform in a table and output the table value to a D/A converter at fixed time intervals.

If a sinewave is encoded in 256 equal period steps the contents of the first 3 steps in the table would be the integer value of:

$$Sin\ \frac{360}{256},\quad Sin\left(\frac{2\times360}{256}\right)\quad Sin\left(\frac{3\times360}{256}\right)\ \ldots$$

The coordinate values are converted to hexadecimal, the maximum and minimum values of which are scaled to the limits of an 8-bit byte (00-FF). To display the waveform, the initial address of the table is selected and the contents at that address transferred to the D/A converter. A timer IC is used to step off the intervals and at each one, the next table value is transferred to the D/A converter.

This method of waveform generation is obviously limited to low frequencies because each step requires approximately 30 μsec of processor time and for 256 steps gives a period of 8 ms or 125 Hz. For higher frequency waveforms, the program table can be loaded into RAM before clocking the data to the D/A converter. The waveform described is quantized into 256 (eight bit) amplitude steps which is usually adequate, but waveforms with a higher resolution are possible at the expense of speed and program-memory space.

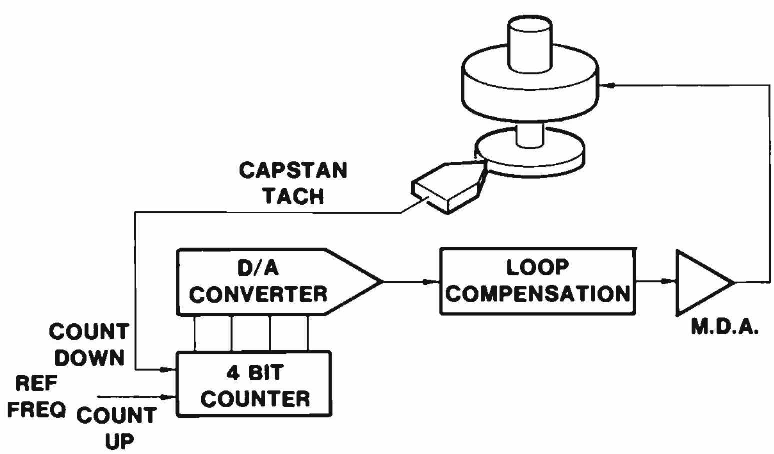


Fig. 147 Wide Range Phase Comparator for Tach Lock Loop

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2. SMPTE RP16:1977, Society of Motion Picture and Television Engineers, 862 Scarsdale Ave., Scarsdale, N.Y. 10583

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9. AUDIO AND AUXILIARY CHANNELS

E. Stanley Busby

Every video recorder has at least one channel for recording program audio. Additional audio channels may be provided, either as replicas of the main channel, or as communications-grade channels for nonprogram use. In addition, a control track channel carries information related to the head wheel rotation and to the video frame rate.

The physical locations of these tracks are shown in the format drawings of Section 4. Details about the control track format and usage are discussed in Section 8.

9.1 DERIVATION OF STANDARD REPRODUCE CURVES Equalization, the process of correcting for deviations from uniform frequency response, is distributed between the record and reproduce circuits. In general, losses attributable to the reproduce process are corrected in the reproduce circuit and vice versa.

The major loss during reproduce is inversely proportional to wavelength for wavelengths which approach the tape coating thickness. Assuming a recording having uniform record current with frequency, and no other losses, the system response has been found to approximate that of a simple RC low-pass circuit. The reproduce system must therefore have an inverse response, rising with frequency.

Based on measurements made on typical tape samples, a standard reproduce curve is selected and promulgated by various standards bodies to effect tape interchange. [1],[2]. The response at high frequencies is expressed in terms of an RC product, or time constant. The response of the reproduce system is given by (1). Values of R_1C_1 range from 15 to 50 μsec. Thicker tape coatings and slower tape speeds require the larger values.

$$\text{Gain dB}=10\log_{10}\left[1+(2\pi f R_1 C_1)^2\right] \quad (1)$$

Low End Roll-Off In some systems, and in some geographic areas, it is common practice to arbitrarily boost frequencies less than about 200 Hz during record, and attenuate them during replay, thus reducing interference from hum fields at power-line frequencies.

The associated reproduce inverse response is given by (2). Again, the response is specified in terms of an RC product. Values of 2000 μsec are typical for quadruplex recorders, 3180 μsec for helical scan recorders, and infinity for quadruplex recorders in parts of Europe.

$$\text{GaindB}=10\log_{10}\left[1+\frac{1}{(2\pi f R_2 C_2)^2}\right]^{-1} \quad (2)$$

Where R_2C_2 is finite, there is a frequency, typically between 600 and 750 Hz, at which the influence of the low- and the high-frequency circuits are equal. It is useful as a test frequency and is obtained by equating (1) and (2) and solving for f. It is given by

$$f=\frac{1}{2\pi}\sqrt{\frac{1}{R_1C_1R_2C_2}} \quad (3)$$

Sin(χ)/χ Correction In addition, other reproduce losses must be corrected. The loss due to the reproduce gap takes the form of

$$\frac{\sin(gf/v)}{(gf/v)}$$

where g = gap length
f = frequency
v = velocity in same units as g

The effective gap length may be found by finding the frequency of zero response (facilitated by using a low tape speed) and applying (4).

$$\textit{Gap length} = \frac{\textit{velocity}}{f_o} \quad (4)$$

Gap length may also be estimated by multiplying the optically measured length by 1.11.

Other losses due to the change in permeability of the core material and eddy current losses versus frequency are also corrected, but are included in both techniques of response measurements (see Section 9.6). The complete reproduce response is given by (5).

$$G(dB) = 10\log_{10}\left[\frac{1+(2\pi f R_1 C_1)^2}{1+\frac{1}{(2\pi f R_2 C_2)^2}}\right]\cdot\left[\frac{\chi}{\sin(\chi)}\right]^2 \quad (5)$$

The $\frac{\chi}{\sin(\chi)}$ component of the response is typically produced by allowing the inductance of the reproduce head to resonate with its associated wiring at a frequency well out of band. Figure 148a shows how the input resistance of the head preamplifier is used to adjust the resonant rise to equal the gap loss at the upper band limit.

Figure 148b shows an alternative resonant boost circuit. Assuming a maximum resonant peak of twice that required at the upper band limit, select R_1; assume $A_1 = 0.7$, $A_2 = 0.97$, and $A_3 = 1.0$; set f_m equal to the upper frequency limit; set $x = \pi \cdot$ gap length $\cdot f_m$)/ velocity; and calculate

$$G_n = \frac{A_n x}{\sin(A_n x)} \quad (6)$$

Set $R = 1/(G_3^2 - 1)$ and find P_1 and P_2 using (7)

$$P_n = \sqrt{\frac{(1+R)^2 - G_n^2 R^2}{G_n^2 - 1}} \quad (7)$$

Then:

$$R_2 = RR_1 \quad (8)$$

$$L = \frac{(A_1P_1 - A_2P_2)}{A_2^2 - A_1^2}\,\frac{R_1}{2\pi f_M} \quad (9)$$

$$C = \frac{A_2^2 - A_1^2}{A_1A_2(A_2P_1 - A_1P_2)2\pi f_M R_1} \quad (10)$$

Need For 240 or 250 Hz Notch on Cue Track On quadruplex recorders the auxiliary audio track is adjacent to a saturated recording whose major component is equal to the head wheel rotational rate. It is customary to put a deep notch in the response of this channel at 240 Hz (250 Hz on PAL and SECAM systems).

Means of Equalization The most common reproduce equalizer circuit is shown in Fig. 149. At low frequencies the amplifier is an integrator which, with the head as a differentiator, forms a system having flat response. At higher frequencies the gain is controlled by R and the rising response of the head results in the desired response. R is usually made adjustable. If the head is treated as a current source, as shown in Fig. 150, it may be thought of as a source of voltage rising with frequency, in series with an inductor, whose impedance likewise rises with frequency. The current into the amplifier is then constant with frequency, except at low frequencies where the resistance of the head winding becomes appreciable compared to its reactance.

C_A in the amplifier feedback path compensates for the head resistance by letting $R_A C_A = L_H/R_H$. The desired overall high-frequency response is produced by subsequent RC response shaping or by use of a delay line as shown in Fig. 151. A good approximation to the desired $1+(2fR_1C_1)^2$ response can be obtained by using delays of from $\frac{1}{20 f_{max}}$ to $\frac{1}{10 f_{max}}$ and gain A of 2 to 10, the shorter delay times requiring the higher gain. The circuit response is given by (11) where T is delay time.

$$\text{Gaindb} = 20\log_{10}\left[1+2(A+A^2)(1-\cos 2\pi f T)\right]^{1/2} \quad (11)$$

Adjustment of Response and Methods of Measurement

Method 1 Either of two methods can be used to adjust the response. An induction coil with low inductance and driven from a resistive source is brought into proximity to

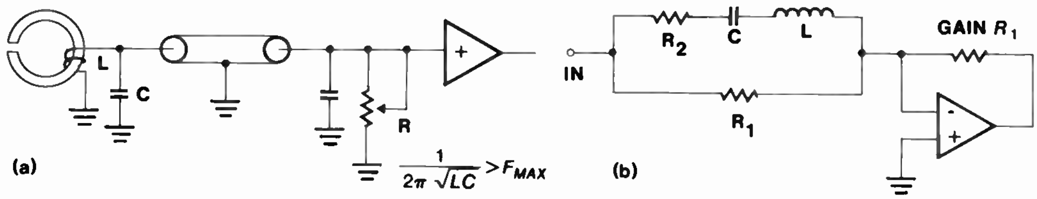

Fig. 148 Resonance Used to Correct for $Sin \frac{X}{X}$ Loss

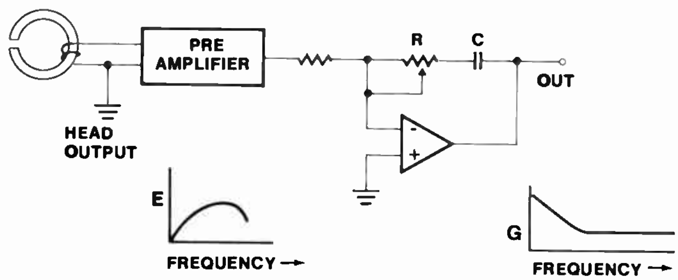

Fig. 149 Typical Reproduce Equalizer

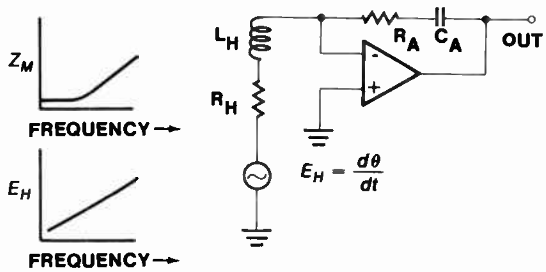

Fig. 150 Current-Mode Preamplifier

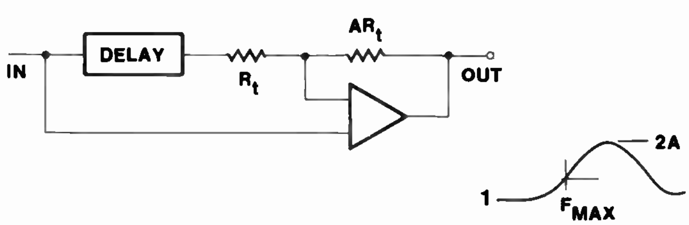

Fig. 151 Delay-Line Equalizer

the reproduce head gap. It provides a magnetic field uniform with frequency. The response obtained at the reproducer output is compared to that calculated by (5) and adjustments made until the response is adequately close.

Alternatively, the test frequency source can have a shaped response which is the inverse of the standard response. In this case, the output response should include only the last term of (5), as sin(*x*) /*x* loss is not a factor in inductive coupling. Losses due to eddy current and permeability versus frequency are operative and will be adjusted out in this method.

Low frequency phenomena due to the finite size of the head's pole pieces are not evident in this method.

Method 2 The replay of a carefully made reference tape provides the means of adjusting the head azimuth angle, the reproduce frequency response, and reproduce gain. Reference tapes can suffer degradation of short-wavelength output with extended use. It is good operating practice to generate secondary reference tapes for routine use.

Occasionally a reference tape is furnished whose recorded track is wider than the reproduce head. At low frequencies this will cause an increase in response which must be accounted for during measurement of response and probably when setting reproduce gain.

Refer to Fig. 152a. The increase in response as a function of frequency is approximated by (12) and can be pronounced at low frequencies

$$\text{Fringing gain (dB)} = 20 \log_{10} \left[1 + \frac{\left(2 - e^{-kd_1} - e^{-kd_2}\right)}{2kW} \right] \quad (12)$$

where $k = \pi \cdot \dfrac{\text{frequency}}{\text{velocity}}$ and W = Head Width.

At frequencies suitable for setting reproduce levels, (12) is sufficiently accurate. At low frequencies, especially on tape having transverse particle orientation,, it can yield significant error. For a more exact formula see Ref. [3].

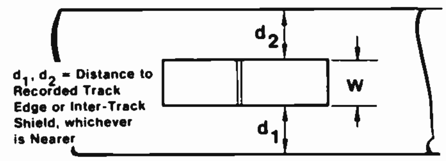

Fig. 152a Dimensions for Fringing Gain Calculation

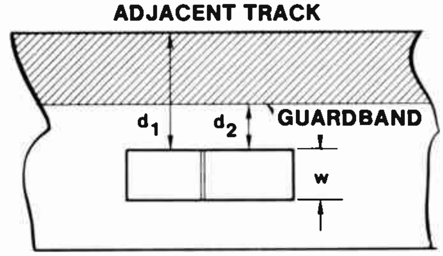

Fig. 152b Dimensions for Reproduce Crosstalk Calculation

9.2 RECORD EQUALIZATION Having standardized the reproduce frequency response, the remaining equalization needed is applied in the record circuitry. The required high frequency boost or roll-off is usually a result of simple first-order RC response shaping, but may employ a delay line. In either case, the circuit must be capable of boosting or rolling off high frequency components, and capable of adjustment.

The remanent magnetization as a result of the record process at high frequencies is strongly dependent on the ac bias level. The bias level is typically chosen to minimize distortion, and then the record equalization is adjusted to correct the resulting frequency response.

Low frequency boost, when applied, is typically produced by fixed components.

9.3 STANDARD RECORD LEVEL The choice of recording level is arbitrary. If too high, then peaks of the program more frequently approach saturation of the medium and are clipped and distorted. If too low, soft passages are obscured by noise. The standard recording level is typically chosen to be 12 to 15 dB below tape saturation, approximately 8 or 9 dB below that level at which 3rd harmonic distortion is 3%.

Record level is specified in terms of surface magnetization of the medium in nanowebers per meter of track width. Values of 100 to 110 nWb/m are typical of video recorders.

Metering Program levels are measured by two different means. The peak program meter (PPM) responds quickly to an increase in level and decays slowly, displaying, in effect, the envelope of peak amplitude. The volume unit meter, standard in the United States, is slower to respond and is more symmetric in its attack and decay.

Operational judgements of program level using a VU meter tend to maintain signal-to-noise ratio constant, and allow distortion to vary as a function of the program peak/average power ratio. Use of a PPM meter tends to hold distortion constant and allow the signal/noise ratio to vary with program content.

9.4 DISTORTIONS

Odd-Order and Even-Order Distortions The tape recording process itself produces distortion products only of an odd-order nature. Even-order distortion products result from any of a number of causes, including:

1. Any fixed magnetic field in the vicinity of the record head, including the earth's magnetic field
2. Any direct current through the record winding
3. Even-order distortion of the bias current source
4. Any residual dc flux remaining on the medium, prior to recording, as a result of erasure
5. Faulty amplifiers

Odd-order distortion products are usually expressed as a percentage of the output amplitude at some specified record level. The absolute amplitude of odd-order products is very closely proportional to the third power of the record level. The phase of the products is such as to correspond to compression of signal peaks.

Pre-Distortion Means To some degree, the system may be linearized by creating, in the record circuitry, odd-order distortion products of opposite polarity to that produced in the recording process. Figure 153 illustrates two methods of doing this.

Intermodulation distortion, the multiplicative influence of one signal component upon another, is also reduced by this *predistortion*. First order intermodulation products are reduced to the same degree as is odd-order harmonic distortion. Second order effects remain unchanged, and third-order effects tend to increase, but are generally below the noise floor and insignificant.

Effect of Bias Level on Distortion For a given gap length and coating thickness, there is a bias level which results in a minimum third-harmonic distortion. With thick coatings and optimum record gap lengths, as in audio recorders, this effect can be significant.

In video recorders, which of necessity use the same head for recording and reproduction, and thin coatings, the effect is not pronounced. Nevertheless, it is typical to set the bias level somewhat greater than that which maximizes long wave-length output, minimizing distortion to the extent possible.

9.5 CROSSTALK FROM ADJACENT CHANNELS The influence of one recording track upon an adjacent one depends on whether they were recorded separately or together. If separately, the crosstalk of a channel into its neighbor may be approximated by (13), referring to Fig. 152b.

$$Crosstalk\ (dB) = 20 \log_{10} \left[\frac{e^{-kd_2} - e^{-kd_1}}{2kW} \right] \qquad (13)$$

where k and W are as in (12). (13) assumes no inter-track shield and is grossly inadequate where wavelengths approach the width of the reproduce head

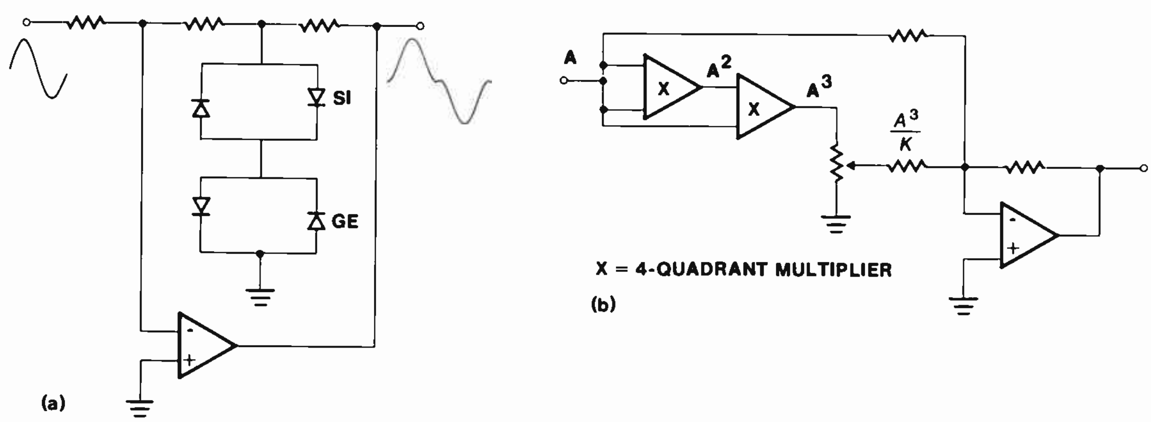

Fig. 153 Methods for Generating Odd-Order Harmonics

structure. Also see Section 2.5, Eqn. 4.

In the case of simultaneous recording, the signal magnetic field penetrates the recording field of its neighbor, and some fraction of it is recorded there.

Cross-talk cancellation in simultaneous recording can be partially effected by injecting the necessary fraction of the record signal, in antiphase, into the neighboring channel.

Cancellation in the reproduce process is done by cross-coupling into a channel a portion of the reproduce signal from its neighbor, in anti-phase. The cancellation is effective only in the mid-range of frequencies, i.e., 250 to 5000 Hz.

The most effective means of cross-talk reduction is the installation of magnetic shields between adjacent heads.

An alternate shield consists of a bar of permeable material positioned close to the reproduce gap. It must be centered on the gap and tangent to the tape path.

9.6 NOISE

External Sources Anything which produces an ac magnetic field in the vicinity of a record/reproduce head contributes to the recorded track when bias current is present and is also coupled into the head during reproduce.

Reel motors generate a field whose effect may be minimized by shielding and/or adjusting the angular position of the motor frame to minimize its field at the audio head. Maximum shielding is effected by wrapping the motor with two concentric magnetic shields, the innermost having moderate permeability and capable of sustaining high fields, and the outermost having high permeability.

The headwheel motor presents a similar problem with similar solutions. The energy involved is generally smaller.

If a picture monitor is mounted in the recorder frame, the fields associated with its deflection yoke are a significant source of magnetic contamination. The horizontal scanning field is the stronger, but only its fundamental frequency is in-band. The vertical scanning field is less strong, but is rich in in-band harmonics.

Shielding of these fields at the source is difficult as the energy absorbed by the shield must be produced by the scanning circuitry. Rotation of the source is out of the question. Typically, the head assembly is encased in a magnetic shield made of a highly permeable material. The best structure is a sandwich of two or more layers of permeable ferrous material separated by layers of copper.

Internal Sources Ideally, the noise produced by moving an unrecorded medium over the reproduce head should exceed amplifier noise by at least 10 dB. Noise with the medium at rest stems from the resistive component of the head impedance and from various noise sources in the preamplifier.

Preamplifier noise can be minimized by concentrating noise contribution at one semi-conductor junction at the input, and optimizing the current through it, considering the source impedance of the head at mid-band frequencies.

Reproduce noise will generally be higher when bias current is applied, consisting, in part, of noise concentrated about the bias frequency and stemming from the granularity of the magnetic particles in the tape. High bias frequencies reduce this effect, but involve problems in obtaining sufficient current.

The bias current must be spectrally pure to avoid the generation of in-band modulation components, which would be perceived as noise.

9.7 AUDIO EDITING When an audio signal is abruptly turned on or off, it has been modulated by a step function. The resulting spectrum is annoying to the ear. The purpose of editing is to attach a new recording to an old one, or replace a section of old recording with new. To avoid audible disturbances at points of commencement and cessation of recording, it is necessary to cause the old recording to be erased gradually, over a period of five to 100 milliseconds, and the new recording to begin just as gradually.

The separation between the audio erase head and the record head requires that changes to the erase current must occur before changes at the record head. On multi-speed recorders this time is a function of the selected tape speed. Figure 154 shows the timing relationship between the envelopes of the erase and bias signals. Some recorders use a modulation envelope resulting from RC charge and discharge, while others use a linear ramp as shown in the figure.

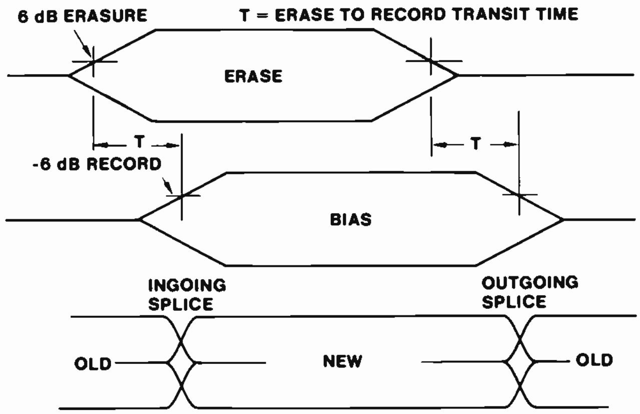

Fig. 154 Controlled Onset and Decay of Bias and Erase for Editing

Spectral components introduced by adequately long modulation waveforms are usually inaudible. Clicks, pops, and thumps heard at or near the edit point usually stem from any of the following sources:

1. dc conditions which produce even-order distortion. (See Section 9.4.)
2. Failure to maintain symmetrical bias and erase waveforms during the ramp-up and ramp-down
3. Very rapid turn-on and/or asymmetry of the video erase waveform that can crosstalk into an audio track, recording a low-frequency thump there
4. Many circuits changing state at the moment of an edit. Power supply voltage changes, small voltage drops in ground wires, and inter-wiring crosstalk can introduce audible disturbances directly into the audio record channel

9.8 SOURCES OF WOW AND FLUTTER Pertubations from a perfectly uniform tape speed can produce frequency modulation of the reproduced audio signal. The slower modulation rates are called *wow* and the faster rates, *flutter*. The chief factor which determines tape speed is the peripheral speed of the capstan shaft. Indirect drive capstans, i.e., belt and pulley, are typically stabilized by a heavy flywheel. Elements which contribute to this source of wow and flutter are:

1. Any rotational element which is not round, or which is not rotating about its center
2. Variations in motor torque
3. Uneven races or balls in the ball bearings
4. Slipping of the tape with respect to the capstan surface

Direct drive capstans typically are fitted with a tachometer disc which generates a frequency which is a multiple of the rotation rate. This frequency is compared to a stable reference and the torque of the motor controlled to maintain equality of these two frequencies (See Section 8.2). Failure of the tachometer disk and the capstan to share a common center of rotation will introduce speed error.

The tape is held tensioned by the torque supplied by the supply reel motor and its servo system, if any. Pertubation in tape tension in this system will be reduced by the gain in the capstan servo loop. This gain is finite and inversely proportional to frequency. At frequencies outside the bandwidth of the capstan servo, usually in the tens of Hz, the tape may be considered to be mechanically *grounded* at the capstan.

Tape is a flexible medium. Pertubations in tape tension cause it to stretch. The resulting change in tape speed at the head is reduced by the ratio of the distance from the head-to-capstan distance divided by the distance of the disturbance to the capstan. Typical sources are:

1. The supply reel and its motor and bearings
2. Turnaround idlers and their bearings
3. The impingement of the video head on the tape
4. Out-of-round or eccentric rotation of the scanner in helical scan recorders

The difference between static and moving coefficients of friction can produce a high-frequency variation in tape speed known as *scrape flutter* or *violin-string effect*. It is very much influenced by the smoothness of the tape and the head.

Scrape flutter and other high-frequency disturbances may be reduced by the introduction into the tape path of a *scrape idler*, just upstream of the record/reproduce head, as shown in Fig. 155. It usually employs jeweled sleeve bearings and must have very low eccentricity.

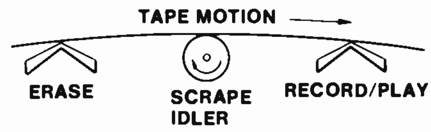

Fig. 155 Inertial Damping of Scrape Flutter

Such idlers are frequently seen on audio recorders, but only occasionally on video recorders.

9.9 INPUT AND OUTPUT CHARACTERISTICS The audio input to a video recorder is typically symmetrical about ground and offers an impedance of greater than 10kΩ. It may be made unbalanced by arbitrarily grounding one input terminal.

The output is typically balanced as well, with unbalanced output available by grounding one output terminal. The output impedance is low, less than 30 Ω, so that connecting a 600 Ω load does not unduly change the output voltage. The output is generally the secondary of a transformer. Output levels of +8 VU are typical at standard recording level with an output capability of +24 to +28 VU provided to accommodate program peaks.

9.10 TIME CODE The auxiliary audio channel is often employed to record a time code which is useful in the implementation of automated editing systems. (See Section 10.2). The time code signal is recorded at fairly high levels to achieve good s/n ratio, unlike audio practice, which is to record at a low level so as to avoid crosstalk of the time code signal into adjacent audio channels.

References

[1] Amer. National Standards Institute, 98.8, V. 98.3, 98.17, 98.20.

[2] International Electrotechnical Commission, Publication 94

[3] Side-Fringing Response of Magnetic Reproducing Heads, A. Van Herk, AES Journal, April 1978, Vol. 26, No. 4.

10. EDITING

E. Stanley Busby

This section deals with the ways and means of editing on a particular video recorder, or a small number of directly connected recorders.

10.1 HISTORY

Mechanical Splicing Early editing was accomplished on 2-inch quadruplex recordings. The recorded tracks were made visible by applying to the tape a suspension of carbonyl iron in a volatile solvent. When the solvent dried, optical magnification permitted identification of the recorded tracks and location of the track containing vertical sync. Using a simple jig, a razor cut was made in the guard band between tracks, just after such a track. Thus any disturbances caused during playback would occur when the vertical relaxation oscillator in a receiver was least susceptible to interference. After discarding the unwanted portion of the recording, the desired portion, cut in the same relative place, was joined using a thin metallic adhesive tape, spanning the width of the video tape. If any of the following conditions were not met, the splice produced a picture disturbance on playback:

1. An odd field had to be joined to an even one, and vice versa. Otherwise, a half-line time-base discrepancy would be created during playback. The horizontal phase-locked oscillators in receivers would then have to rephase, an operation extending well into the active picture area, and producing a visual effect known as a twitch.
2. The phase of the control track signal on the two recordings relative to the recorded tracks had to be the same. If not, mistracking could occur during playback, resulting in interference from adjacent tracks while the capstan servo reacted to the change.
3. With the early machines, 50% of the splices were unsuccessful, as there was no clear way to identify even and odd fields. Before long, a sharp flux reversal was superimposed on the control track recording, coincident with the beginning of an even field. This facilitated the optical location of a suitable splice point. Still later, the flux reversal was reduced in frequency to 15 Hz (60 Hz systems) or 6.25 Hz (50 Hz systems) to reflect the cyclic relation between color subcarrier frequency and horizontal and vertical rates. At the best, the yield of good splices was poor, and in no cases could the audio, recorded about nine inches downstream from the video, be edited at the same temporal location as the video.

Electronic Editing

Several developments led to an electronic analog of the mechanical splice:

1. A video erase head, tilted at an angle, and so timed that erasure began within an appropriate guard band.
2. Circuitry to separate the control track pulse from its sine wave component.
3. Timing circuitry to start video recording about 0.6 sec. after the start of erasure.
4. Means to alter the playback timing so that synchronism was established at the reproduce head rather than at the system output.
5. Timing circuitry to control the start of audio erasure and the start of audio recording.
6. Timing circuitry to control the inverse of items 3 and 5, i.e., the process of coming OUT of record.

Even with all the above, there remained the severe limitation that the video to be inserted into a recording must be of the same duration as that which was to be replaced. Further, the exact time of the commencement of recording was related to a human function, the pressing of a button.

To deal with the latter, devices were developed to allow rehearsal of a proposed edit, the frame-by-frame adjustment of the proposed edit point, and the actual performance of the edit. Timing of the edit was dictated by a tone burst recorded on the auxiliary audio channel. The location of the burst could be modified by an integral number of frames from a control panel, tested for suitability, and finally committed to tape. Provision was also made for the repetitive addition of a few frames of video to permit a mode of operation similar to that of film animators.

When the source of the video to be recorded was the playback of another video recorder, the relative timing of the two elements of the edit was provided by adjusting each machine's position using its tape timer as a reference, and starting them simultaneously. This method was highly susceptible to inaccuracy.

10.2 TIME CODE EDITING The need for fast and accurate conjunction of video signals from two or more sources is met by the recording of a digitally coded signal on each auxiliary audio channel. Promulaged by the Society of Motion Picture and Television Engineers, it is called the *time and control code*. Each frame of a recording is uniquely defined by an 80-bit coded signal. 32 bits are used to define the frame, expressed in hours, minutes, seconds and frames, 32 bits are reserved for undefined purposes, and a 16 bit sequence defines the frame boundary and includes a bit sequence from which the direction of tape movement can be discerned. The channel coding is *bi-phase mark*, in which each bit cell is delineated by a flux reversal, and a binary *one* is defined by an extra mid-cell transition. Since the frame rate of NTSC color television is $30 \times 1/1.001$ Hz, the indicated time falls behind real clock time at the rate of several seconds per hour. To compensate for this, two frame counts are skipped over each minute except every tenth minute. This adjustment, which is optional, is called *drop frame*. It is not necessary in 25 frame systems, whose frame rate is exact.

The time code signal is recoverable over a wide range of tape speeds, about one-fifth normal speed to 50 times normal. Even so, helical scan recorders offer the capability of reproducing a single field while the tape is stationary, obviating recovery of the time code longitudinal recording. To provide frame identification in this case, Vertical Interval Time Code (VITC) may be injected into the video signal path during recording. One iteration of the code occupies one horizontal interval, and is typically recorded on two non-adjacent intervals during vertical blanking.

On most helical scan recorders, VITC may be recorded using either the dedicated sync head, which records only the vertical sync interval, or the main video head, which records all other video, including much of the vertical blanking interval. If recorded on the sync channel, the advantage is obtained that time code may be recorded independently of the video head, which is often able to move to adjacent tracks (see Section 8.9, AST for C-format Machines), may not be scanning the track identified by the sync channel. If recorded on the video channel, there can be no doubt that it accurately identifies the frame, but it must be applied at the time of video recording, with no possibility of independently altering it later.

In both time codes, numbers are expressed in binary-coded decimal (BCD), using four bits per digit. Since the tens of frames and tens of hours digits never exceed two, and tens of seconds and tens of minutes digits never exceed five, there are six bits of the 32 time-code bits that are not needed to express time. Several of these are used to convey other information:

1. In NTSC, whether or not drop-frame time correction is being used in the counting sequence.
2. Whether or not the counting sequence has been phased to reflect a particular horizontal-to-subcarrier timing relationship.
3. Whether or not the user bits contain coded alphabetic characters.

4. A parity bit, used to cause the total number of transitions, after coding, to be even. This is a necessary, but not sufficient requirement to edit a time code track without loss of data during subsequent decoding.

The complete time code specifications may be found in Refs [1],[2].

10.3 IN-MACHINE EDITORS The advent of microprocessors greatly increased the density of a logic functions available within a video recorder. Much of this logic capability is applied to editing requirements. Two modes of editing are typically offered, INSERT and ASSEMBLE. The INSERT mode implies that some previously recorded element is totally replaced. Here, a control track recording is assumed to exist, and the recorder uses it to control the tape position during the recording, just as it would in playback. In the ASSEMBLE mode, it is assume that a new recording is being added at the end of an old one, and a new control track is recorded, phase-coherent with the old one. In helical scan recorders, erasure of the tape into which the new video recording is to go is provided by a *flying erase head,* mounted on the rotating scanner, and located just ahead of the record head, to pave the way. Many video recorders include the ability to reproduce time code, and synchronize their tape movement with an external reference. When the specified frame is approached, all the precursory actions are taken to cause a splice to occur at the specified frame number, and cease at another specified frame number. Typically, video and audio splice points are separately definable.

Communications with a video recorder that is a peripheral of an editing system is accomplished with a high-speed serial interface. Data which are time-related are transferred within a frame interval. The video recorder is expected to be able to position its tape at a specified frame, synchronize its tape movement with other recorders, begin recording at a specified frame, and cease recording at still another specified frame. Many other machine functions may be executed via the serial interface.

The serial interface may either be an external accessory to the recorder, or, as is increasingly the case, contained within the the recorder's electronics.

References

[1] EBU TECH 3097-E, Time-and-Control Codes for Television Tape Recordings, (625 line systems). Technical Centre of the E.B.U., Bruxelles, Belgium, April 1972.

[2] ANSI V98.12M - Time and Control Code for Video and Audio Tape for 525-line/60 Field Television Systems, Amer. Natnl. Standards Institute, New York, N.Y. 19981.

CONTRIBUTORS

H. Neal Bertram

Neal received a B.A. from Reed College Portland, OR. in 1963. In 1968 he completed his Ph.D. at Harvard University, MA. From 1968 to 1985 he was employed by the Ampex Corporation in Redwood City, CA to work on fundamental problems in magnetic recording. While at Ampex he engaged in both theoretical and experimental studies of particle interactions, ac bias recording, media noise, the recording process for particulate and thin film media, high density and multi-track head design, and head saturation. From 1978 to 1985 he was manager of the recording physics section of the research department (ATD) at Ampex and in 1984 became a Principal Engineer. In 1985 he joined the University of California at San Diego as an Endowed Chair Professor in the Electrical Engineering and Computer Sciences Department associated with the newly created Center for Magnetic Recording Research. At UCSD he has created a graduate course in magnetic recording which includes two quarters on the theory of recording materials and the recording process and a third quarter laboratory course on magnetic recording measurements. His current research with graduate students includes record process modeling, noise mechanisms and micromagnetics of recording media. He is a cellist by avocation and an ardent hiker and camper.

E. Stanley Busby

Stan falsified his age to get a First Class Radiotelephone Certificate, and stood transmitter watch while attending high school in Portsmouth, VA. At 18, he enlisted in the Army Air Corps, transferred to the Signal Corps. and served with the Armed Forces in Manila and Okinawa in World War II. Following the war, he worked in radio broadcasting until joining Ampex in 1960 as a field service engineer. After three years Stan became, by default, a salesman with the Washington, D.C. office, transferred to Redwood City, to become an instructor in the Video Training Department, and then to AVSD Engineering where he has remained ever since. A Senior Staff Engineer, Stan has been involved in both analog and digital approaches to video, audio and editing projects too numerous to list.

He is a computer buff, a licensed pilot, a lover of baroque music and a some-time photographer.

Harold V. Clark

After getting his Bachelor's Degree in Physics and Mathematics from Union College in Lincoln, Nebraska, Hal spent the period from 1950 to 1952 with the U.S. Army, and attended Stanford University from 1952 to 1955, earning his M.S.E.E. He came to Ampex in 1955, and was first involved in the development and testing of loud speakers for the Todd AO stereo system.

Hal ran the Standard Tape Lab for a year, then moved into Video Engineering to work on the drum motor servo system which subsequently became known as Intersync. Over the years he has been intimately involved with servos for quadruplex recorders VR-1000, VR-1100, VR-2000, AVR-1, AVR-2, and ACR-25 and numerous digital developments.

A Senior Staff Engineer, his hobbies include motor cycling, flying (airplanes), ham radio, and gardening.

Michael O. Felix

Michael received his Bachelor of Science Degree in Telecommunications from City and Guilds College in London, England in 1942, and then served as an officer in the Royal Air Force from 1942 to 1947, maintaining radio equipment in fighters. From 1947 to 1954 he was with British Telecommunications Research, where he developed the first portable 160 MHz transceivers, and spent 1955 in Sarawak, surveying and installing a radio linked dial telephone system.

In 1955, Michael emigrated to Canada and became part of a Canadian Westinghouse team that developed the first wideband tropospheric scatter system. He joined the Video Engineering Department of Ampex in 1960, making many outstanding contributions, most notably, the analysis of the FM system used to this day in all video tape recorders throughout the world.

From 1965 to 1970 he served as Chief Engineer of the Videofile Document Storage and Retrieval System, and from 1971 to 1976 headed Engineering in the Audio Video Systems Division. He was made Chief Engineer of the Data Systems Division in 1976, General Manager of the Advanced Technology Division in 1982, and was named a Vice President in 1983. Michael retired in July 1985.

Hobbies: Gardening, photography, home remodeling, occasional golf.

Charles P. Ginsburg

After working in the radio broadcasting industry for nearly a decade, while gaining a Bachelor's Degree in a combination of mathematics and engineering from San Jose State College, Charlie went to work at Ampex at the beginning of 1952. His specific assignment was to attempt to develop a practical method for recording television programs on magnetic tape. He gradually acquired a small project team, and the demonstration in 1956 of what they developed revolutionized television broadcasting.

Because of what his group accomplished, Ginsburg received international recognition, and many awards. The most outstanding were: the David Sarnoff Gold Medal of the SMPTE in 1957; the Vladimir K. Zworykin Television Prize of the IRE (now the IEEE) in 1958; the Valdemar Poulsen Gold Medal of the Danish Institute of Technical Sciences in 1960; the Howard N. Potts Medal of the Franklin Institute in 1969; and the John Scott Medal of the Board of Directors of the City of Philadelphia in 1970. In addition, he was elected a Fellow of the IEEE; a Fellow, then an Honorary Member, of the SMPTE; an Honorary Fellow of the Royal Television Society; a Life Fellow Member of the Franklin Institute; and a Member of the National Academy of Engineering.

A vice president of Ampex since 1960, Charlie was the organizer and the Chairman of the SMPTE Study Group on Digital Television since the decision was made in 1974 to establish such a group. He retired from Ampex at the end of January, 1986.

Beverley R. Gooch

Bev Gooch started a radio, television, and high-fidelity service while still in high school in Nashville, Tenn., and expanded it to include the design and installation of magnetic tape recorders and special sound effects equipment. From 1954-1959, as a side-line to doing custom installations for recording studios, he developed a longitudinal video recorder which he demonstrated to a number of parties, including the 3M Company and Bing Crosby, and finally sold the recorder and the rights to Brush Instruments in 1959. Bev worked for Brush on video recording and head design and in 1962 he came to Ampex. With 24 years at Ampex in audio and video head design, in addition to his prior experience, and with 12 issued patents relating to heads and magnetic recording, Bev is recognized worldwide as an outstanding authority in his field.

A Principal Engineer, his hobbies are restoring ancient film cameras and tape recorders.

John W. King

In 1950, Pan American Airways replaced its manually-operated radio telegraph air-to-land communications with pilot-operated radio telephone, enabling them to release a number of radio operators. Eight of them came to Ampex, and one of these was John King. First in Manufacturing, then in Quality Control, then in Special Products, John's entry into Engineering found him involved in the development of the UNQ-7 Submarine Sonar Recorder for the Navy in 1954. Early in 1955, he joined the VTR project, in which he served successively in development, field training of customers, and eventually in all phases of quadruplex head assembly problems and development. After 25 years in this latter activity, John retired in 1980.

William McSweeney

Born in Ireland, Bill was educated in London receiving Higher National Certificates in both Electrical and Electronic Engineering in 1961 and 1963, respectively. After completing additional courses in the physical sciences, he was elected MIERE (Member of the Institute of Electrical and Radio Engineers). With a background of television experience in the British Relay Corporation in London, Bill joined Ampex in Redwood City in 1967. He worked on reference timing circuits and signal systems on quadruplex recorders AVR-1, ACR-25, and AVR-3 and helical recorders VPR-2, XVR-2 (wideband television x-ray recorder), VPR-80, -5, -6, and XVR-80.

Bill left Ampex to join Cartridge Television Inc., in 1971. After two years at CTI, he spent time with Consolidated Video Systems & Echo Science, and returned to Ampex in 1977.

Bill is a Senior Staff Engineer in AVSD, an erstwhile soccer player, and now devotes most of his leisure time to golf.

Reginald W. Oldershaw

Graduating from the University of Essex, England, in 1961, with a Higher National Certificate, Reg worked at the Plessey Corporation from 1961 to 1967, both in London and in Havint. With Ampex in Redwood City since 1967, he designed servos for the quadruplex recorders AVR-1 and ACR-25, and was the Project Engineer in the later phases of the ACR-25 and the quadruplex AVR-3. Reg was involved in the AVR-2 auto-tracking development, and the AST on early helical digital VTR projects. He was Project Engineer on the helical recorder VPR-80, and his recent activities have been with proc amps, time-base correctors, and drop-out compensators.

On eight patent applications, of which four have been granted, Reg was sole inventor on one and co-inventor on the others.

Reg is an accomplished builder - he put up his own cabin in Bear Valley, Calaveras County, California - and an avid skier.

Robert H. Perry

After getting his Bachelor's Degree in Chemistry from Baylor University in 1948 and his Doctorate in Organic Chemistry from the University of Texas in 1952, Bob worked for Esso Research and Engineering Company (now Exxon) from 1952 to 1967; Polaroid Corporation from 1967 to 1969; and the Magnetic Tape Division of Ampex since 1969. He has received 18 patents, mostly as a sole inventor, and has written a number of technical papers in recent years, primarily on magnetic tape. His field of expertise includes hydrocarbon oxidation and catalytic conversion processes, polymer chemistry and magnetic tape technology.

Bob considers one of his finer achievements to have been reaching the position of first chair in the trumpet section of Waco High School, one of the largest award-winning bands in Texas. His most avid avocational interest is exploring the back roads, mountains and forests of California on a motorcycle. Bob is the Manager of Chemical Analysis for the Magnetic Tape Division of Ampex.

Raymond F. Ravizza

Ray received his B.S. degree in Electrical Engineering from Cal Poly in 1966, and joined the Research Department of Ampex where he worked on laser and electron beam recorders. In addition, he attended the University of Santa Clara and earned his MSEE Degree in 1972.

He transferred to AVSD Engineering in 1974 and became involved with the AVR-2 audio circuit design. Shortly thereafter he began working on the development of the VPR-1 AST servo system, followed by the implementation of the continuous slow motion and variable speed shuttle improvements to this product. Ray's next task involved the design of the SMC-60/100 series slow motion controllers. Following this he was assigned to be helical recorder VPR-2B project engineer, and also contributed to the design of the reverse slow motion AST and transport servo systems. These efforts earned him the Poniatoff Award in 1980.

In 1981 he began the design of the AST servo and sync processor electronics for the VPR-3 helical recorder. After completing these tasks Ray designed the hardware and software for the slow motion controller serial interface to the VPR-3. Currently he is involved with the design of the ACR-225 cassette selection system and bar code reader systems.

A Senior Staff Engineer, his hobbies include restoring classic Chevrolets and home remodelling projects.

Dennis M. Ryan

After receiving his Bachelor's Degree in Mechanical Engineering from Texas A&M in 1960, Dennis worked at Collins Radio and Triple S Dynamics, both in Dallas. In 1968, he joined Ampex and was engaged in packaging and mechanical design of the VR-3000 quadruplex recorder, and helical recorders, VPR-1, -2, and -80. In 1985, in recognition of his outstanding work in mechanical design for application in digital videotape recording, Dennis was given the Alexander M. Poniatoff Gold Award.

Dennis was Ampex' chief representative in the mechanical definition of the SMPTE Type C format, and at the time of this writing, is performing that same function with respect to the new Type D-1 digital broadcast VTR standard. A Principal Engineer in AVSD, his hobbies include flying ultralight airplanes, and motor cycling, which he has been doing daily for the last 25 years.

David Trytko

In 1978 David received his Bachelor of Science Degree in Electrical Engineering from Purdue University and joined the Audio Video Systems Division of Ampex in Redwood City. At the same time, he became an Honors Co-Op student at Stanford and received a Master's Degree in Electrical Engineering in 1982.

Initially with the Timebase Corrector group, he was involved in the design of the TBC-2 and the TBC-3, and was the Project Engineer on the TBC-80 and the TBC-6. David joined the Ampex Digital Optics (ADO) engineering team in 1985. A Staff Engineer and a native of the Midwest, he is now happily settled in the Bay Area. His hobbies are sports, electronics, and music.

Steven D. Wagner

Steve received his Bachelor's Degree in Electrical Engineering from the University of California at Berkeley at the end of 1979, and immediately went to work at Ampex. Involved in the development of digital time base correctors and digital video processing from the start, he was the Project Engineer on the Zeus-1 processor, and designed the digital signal processing circuits for off-tape clock generation and variable-speed playback.

A Staff Engineer, Steve is an amateur musician who plays several instruments, including jazz piano, keyboards, and drums. He is a hiker and a skier, and has just taken up darts. He recently put together his own set of golf clubs, and is dedicated to breaking 100 as soon as possible.

Photography: Ampex Photo Department
Phototypesetting: Beverly Schmidt
Concept, Layout, and Art: Gerhard Holz

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