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Magnetic Recording Media

Part I: Care and Handling of Magnetic Tape

Part II: Principles and Current State of the Art

Part I: Care and Handling of Magnetic Tape

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INTRODUCTION

Magnetic tape recording plays an important role in many information storage applications. Those people involved with the recording and storage of this type material should be aware of the conditions and procedures that will help ensure the best overall results. The purpose of this section is to give some of the guidelines to achieve good tape life and tape performance. Although this information is aimed at the video tape recording field, it is basically applicable to other magnetic recording areas.

BASIC INFORMATION

Magnetic recording has proven to be a very viable, versatile, and reliable form of storing information. The electromagnetic media used in recording tapes are capable of retaining the signal for indefinite periods of time. The recorded signals will remain virtually unchanged for decades unless they are intentionally erased. Those problems that have been encountered with magnetic recording are mostly physical in nature, due to improper handling or storage conditions. These problems can be caused by malfunction of machines, improper operator care, or poor environment in either the operations area or storage area.

The following information is intended to help in achieving optimum tape performances by hitting upon certain key points with as little rhetoric as possible to simplify the reader's future reference to parts of this chapter.

The Recording and Operations Area Environment

Foreign debris from the environment is one of the reasons for the cause of dropouts, scratches, machine parts wear, head life, and tape life. This warrants important consideration today, and is becoming more important as the recording density on tape increases.

1. The area in which tapes and machines are used should approach "clean room" conditions, such as those found in main frame computer tape installations. This degree of air filtration, though ideal, is not realistically achievable in many video tape operations. It is recommended that at a minimum the filtration used must at least meet the efficiency rating of 90 percent based on the National Bureau of Standards Dust Spot Efficiency Test—Atmospheric Dust. Qualified air conditioning and air filtration firms are aware of the requirements to satisfy this need. The airflow system should be designed to maintain a positive pressure in the recording area.

This prevents dust particles from floating into the room from other locations. In addition the duct work sizes and placement, leading to this area, should allow the necessary amount of air flow to maintain the proper temperature and humidity control, without having air velocities at a level high enough to blow settled dust and debris around the room.

2. The temperature should be controlled at approximately 70 °F plus or minus 5%, and the relative humidity at 50% plus or minus 20%. Without this control the risk of head clogging, stiction, and higher headwear are increased. The old cliche is still true "what is comfortable for humans is a good environment for the tape."
3. To avoid inadvertent contamination of both the tapes and machines, smoking, eating, and drinking should be restricted to certain areas and preferrably out of the recording locations.
4. Special attention must be given to the floors in or near the recording area, as they are a source of debris due to pedestrian traffic. Cement flooring must be sealed and tile floors should not be waxed. Both should be mopped clean on a routine basis. The use of indoor-outdoor type carpeting that contains anti-static material is acceptable and may be most desirable, depending on the needs of an operation. The carpeting helps reduce room noise from equipment, and affords an atmosphere conducive to good operator practices. The use of industrial vacuum cleaners is recommended on carpeting or floors, and it should be done on a regular basis. The exhaust from these units should be located outside the recording area.
5. To aid in the reduction of debris due to pedestrian traffic, the recording area should be located such that it is not a normal passageway to other parts of the operation. This not only improves the cleanliness of the area but avoids continual distraction of the tape machine operator's function.
6. During times of construction in any area of the facility, the frequency of cleaning should be increased substantially. The area under construction should be sealed off with plastic sheeting as best as possible. Surprising as it may seem, cement dust can get through filters that water will not.
7. The tops of equipment and other exposed surfaces should be cleaned on a periodic basis to maintain the integrity of the operations area. This procedure will also give clues as to how clean the envrionment is in the area. The more dust and debris found during this routine is an indication of the amount of dust and debris that has found its way onto the tapes and into the recording equipment.

Operating Practice Recommendations

The video tape operations in a facility are usually involved with more than one type of tape machine; namely reel to reel type and cassette type.

The differences from a tape life or reliability point of view are only the questions of who or what is handling the tape during thread up, how exposed is the tape when on or off the machine, and the tape path conditions. The cassette approach virtually eliminates the human handling of the tape, and reduces the exposure to atmospheric contamination; however, the mechanical threading mechanisms require attention as well as the condition of the tape path. The recommended environmental conditions apply to both type systems. Before proceeding, the next comments may help put things in a better perspective.

People involved in any video tape recording operation, at some point, may ask whether all the emphasis put on cleaning, handling, and environmental control really accomplishes anything; that is, in other terms, "familiarity breeds contempt." Fig. 1 gives a good picture of the relative sizes of what is being dealt with. Not only is this debris capable of causing large drop-outs in the area they are located on the tape; but some of these particles, when wound into a tape pack, may cause impressions into adjacent layers which in turn will result in additional drop-out activity.

Wallace's law on signal loss due to head to tape spacing theoretically indicates that compacted debris contained in a one pint jar, if equally distributed, would be sufficient to put every video tape ever produced out of manufacturers' drop-out specifications.

Good housekeeping and operation practices are very important to a successful video tape operation.

Following are some of the operational recommendations that apply to the handling of reel to reel and cassette type video tape recording formats.

1. The components in a video tape machine that contact either the front or back side of a tape, should be cleaned before each tape is threaded to make a recording or playback. The recommended cleaning fluids are Freon TF (a DuPont trademark), Genesolve D (an Allied Chemical Trademark), isopropol alcohol, or other cleaners recommended by the machine manufacturer. The cleaning should be accomplished by applying the liquid to a lint free cloth, such as Texwipe (trademark), and gently rubbing the tape path surfaces with the dampened material. During this procedure extreme care should be exercised in cleaning the video heads. They can be easily broken or damaged with excessive pressure, particularly in the case where ferrite materials are used. Ferrite is the head material used in most all current day helical machines and in many rebuilt quadruplex heads. Since the video heads will not withstand a strong scrubbing action, compared to the other transport areas during cleaning, the stronger solvents such as isopropol alcohol, or machine manufacturers recommended solvents (usually Xylene type), are the best choices for removing debris build up on the video heads. They tend to help soften material buildup in addition to acting as a wash.

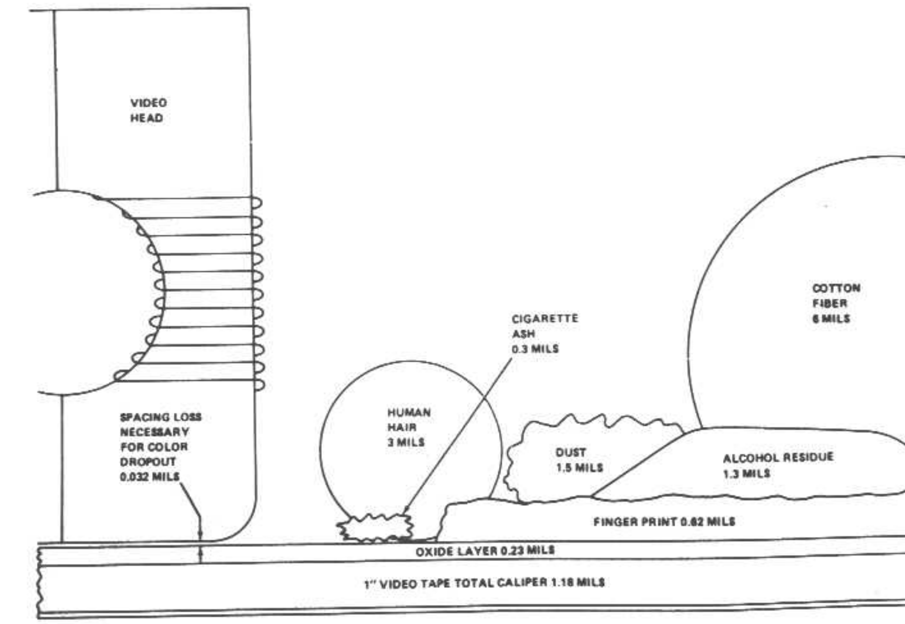

Fig. 1. Debris perspective on 1" video tape.

2. The cleaning of the capstan and the capstan pinch roller are especially important for two reasons. Any dirt or debris build up on these areas will cause impressions in the tape on each revolution that can cause drop-outs through a long period into the roll. Also the accumulation of material in this area may reduce the frictional pressures on the tape which are needed to maintain proper linear tape speed control. One word of caution: the material used in the pinch roller can be adversely effected by some cleaning solutions. The machine manufacturers recommendations should be followed for cleaning the pinch roller.
3. Cleaners, other than Freon TF or Genesolve D are relatively slow in evaporating, so give ample time for the transport to dry before threading the tape. This usually means about 30 seconds.
4. The video drum (scanner assembly) on helical machines have tape edge guiding surfaces that may accumulate debris. These surfaces need extra cleaning attention to ensure smooth tape handling and good interchange with other recordings.
5. The tape reel is specially designed for transporting magnetic tape. The reel should always be handled by the hub, which is the strongest portion of the reel. (See Fig. 2.) The reel flanges are designed to protect the tape edges, not to guide the tape. A reel should never be carried by the flanges. Handling the tape by the reel flanges or dropping an unprotected reel can bend the flanges. If the tape is rubbing against the flange of the reel, either the reel flanges are bent, or the reel pedestal or guides require adjustment. Avoid squeezing the flanges of a reel when putting on or taking off the transport.
6. The take-up reels should be cleaned at the start of each day. The tape winding surface of the hub and the inside surfaces of the

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INTRODUCTION

The broadcast of audio and video programming is greatly facilitated by the ability to store and recover information, and sometimes erase or alter it. Despite the availability of photography and other means of storing images, sounds and symbols, magnetic recording has enjoyed a long pre-eminence in these applications because of a number of features:

1. Easy recording by inexpensive transducer (head)
2. Stable long-term storage
3. Simple playback process with good signal-to-noise ratio, possibly using the same head as for recording
4. Easy erasure and editing or updating, especially important in broadcast studio environment
5. Relatively high surface information density
6. Thin flexible media, which can be rolled up (unlike phonograph record or video disk) for extremely high *volume* information density
7. Inexpensive media—high-quality magnetic video cassette tape is available at a lower cost per square inch than the transparent tape used to mend books!

NOTE: Superscript numbers refer to references at end of the chapter.

This article will attempt to give a brief overview of the basic physical principles involved in magnetic recording, some of the leading types of recording materials, and the directions of current research and development. More thorough discussions of various aspects of recording theory and practice are available[1,2].

BASIC PRINCIPLES

Audio and video signals are handled as electrical quantities (voltages and currents); some fundamental physical laws that relate electrical and magnetic phenomena, and therefore make magnetic recording possible, are shown in Fig. 1. The changing flow of electrical current in the recording head gives rise to a changing magnetic field, which imposes a magnetization pattern on the recording medium (e.g., tape). During playback the reverse process occurs, as the changing magnetic field experienced by the head, due to the passing recorded magnetic surface, induces a signal voltage.

The inductive nature of the playback head dictates that only a *change* in the magnetic field experienced by the head leads to an output signal. Further, a faster change produces a greater output amplitude. A consequence of this is a frequency dependence in the output amplitude. Fig. 2 shows this dependence, for sinusoidal signals recorded at a constant depth and magnetic ampli-

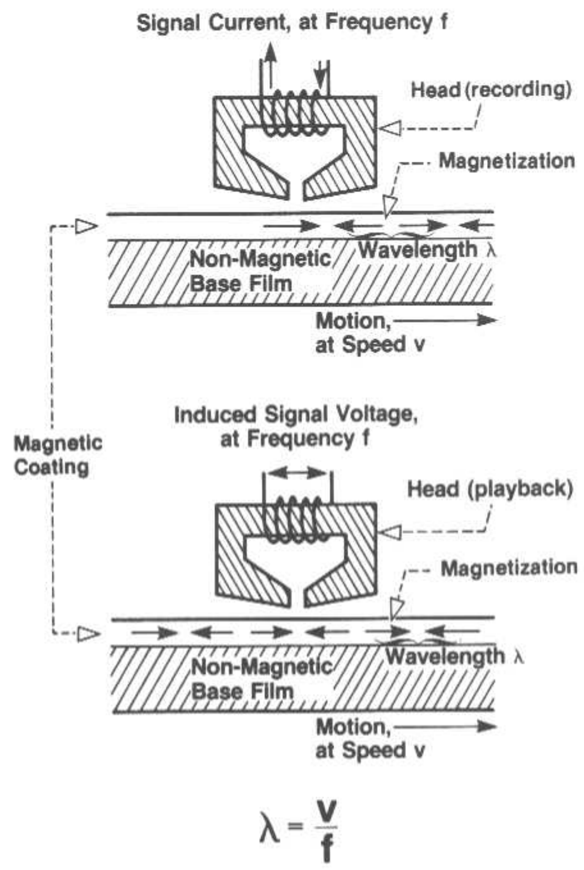


Fig. 1. The elements of magnetic recording and the relationship between signal frequency, transport speed, and recorded wavelength.

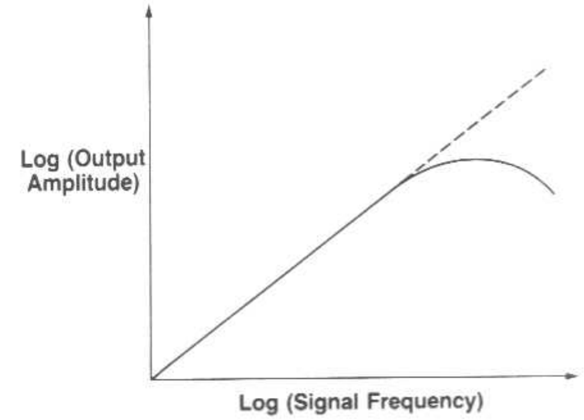


Fig. 2. Logarithmic plot of output amplitude vs. signal frequency, for sinusoidal magnetic recording at constant magnetization amplitude and depth. The slope of the linear rise is 6 dB per octave.

tude in the medium. The output is proportional to frequency over a large range; the fall-off at high frequencies (high recording densities or short recorded wavelengths) is due to signal loss from a number of sources which will be discussed later. The frequency dependence of the output is largely compensated for in many applications by the use of a frequency-dependent electronic gain; this process is called equalization.

The performance of a magnetic recording system depends, to a large degree, upon the magnetic properties of the material used to make the recording medium. The most significant properties are explained in Fig. 3, which shows a plot (called a hysteresis loop) obtained by placing a sample of the material in a varying magnetic field H and measuring its magnetization intensity M. The points at which the plot crosses the vertical M axis define the quantity known as the *remanent magnetization* M_r, which describes how much magnetization intensity the material is able to retain in zero field after being magnetized by a saturating field. The quantity usually specified (in the cgs system) is $4\pi M_r$, also designated as B_r, which is called the *retentivity*. The ratio of M_r to the *saturated magnetization* M_s is called the *squareness;* it helps to define the shape of the loop and therefore the recording properties of the material. The points at which the loop crosses the horizontal H axis define the *intrinsic coercivity,* often referred to as simply the *coercivity* and designated by H_c. This is the field needed to reverse half of the magnetization after saturation in one direction, resulting in zero net magnetization. The steepness of the plot as it goes from one direction of magnetization to the opposite one relates to the ability of the material to record a signal with sensitivity and precision. A quantitative measure of this steepness is the *switching-field distribution* (SFD), described in Fig. 4.

The response of a magnetic recording material to an applied field is clearly non-linear (see Fig. 3). In many applications, it is desirable to remove

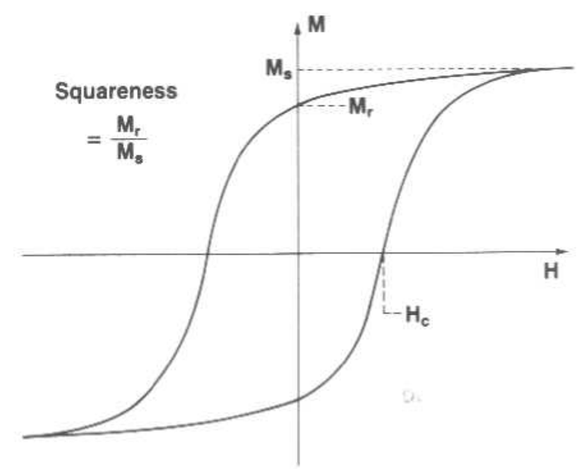


Fig. 3. Plot of magnetization M vs. applied magnetic field H, for a typical magnetic recording material.

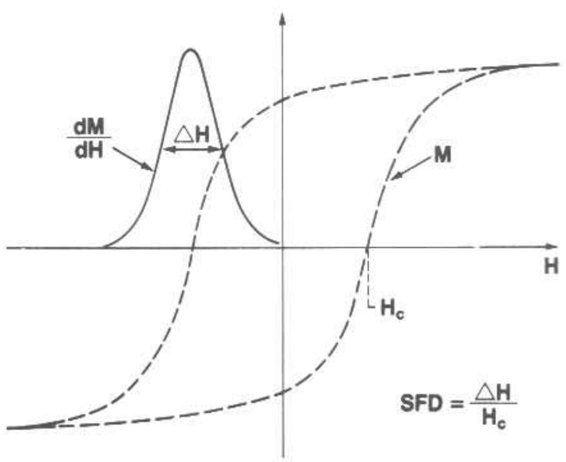


Fig. 4. Plots of magnetization M (broken line) and first derivative dM/dH (solid line) vs. applied field H. Width ΔH, used in the definition of the switching-field distribution (SFD), is measured at half the peak height.

this non-linearity so that the recorded magnetization can be made proportional to the signal current. The needed linearization of the response is accomplished through the technique known as ac-bias, in which the desired signal current is added to an alternating current of much higher frequency and amplitude before being applied to the recording head. The process and the result are diagrammed in Fig. 5; more complete discussions are available elsewhere[2,3]. The recording material is taken through a number of progressively smaller hysteresis loops as it leaves the vicinity of the recording head gap and is left in a state in which the remanent magnetization is very nearly proportional to the signal. The use of ac-bias is important in applications where the waveform read back must be an accurate reproduction of the input waveform, particularly in audio recording.

In some applications, the recorded information is contained in the timing of the zero-crossing points of the signal, rather than in the shape or amplitude of its waveform. Two of these applications, which do not usually utilize ac-bias, are digital recording and frequency-modulation (FM) recording. Digital recording is very simple in concept, although the applictions can be very sophisticated. Digital recording seeks only to convey reliably the strings of binary digits (abbreviated as "bits"), 0's and l's, that make up the information used in computers and other data-handling devices. Fig. 6 shows a simple scheme for doing this. In practice, more complex procedures are used; some additional magnetic transitions are used for timing purposes and some convey information that is redundant but needed for the detection and correction of errors. Er-

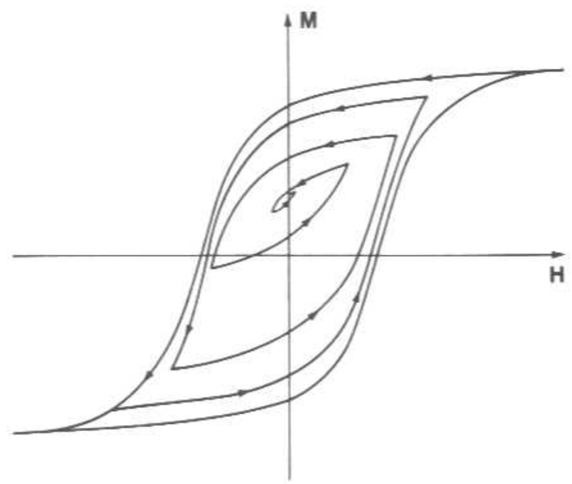


Fig. 5. The principle of ac-bias. As a specific small area on the tape moves away from the recording head gap, it is subject to a high-frequency bias field of decreasing amplitude. This causes its magnetization to vary as shown by the arrows, and to be left in a final state proportional to the signal field upon which the high-frequency field is superimposed.

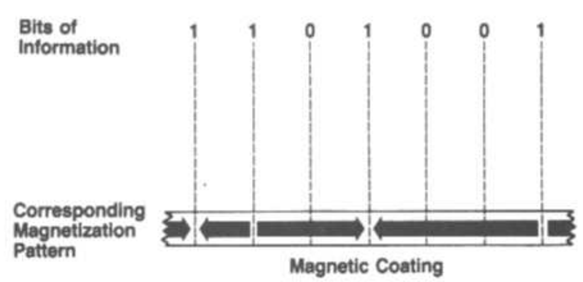


Fig. 6. A simple form of digital recording, in which 1's are encoded as magnetic transitions and 0's as the absence of transitions.

rors may occur through excessive random noise or through defects in the surface of the tape or disk.

Digital recording, in addition to its obvious computer applications, is increasingly being used to replace analog recording techniques in audio and video applications[4,5]. The original signal is measured at precise intervals and the measurements expressed as a series of numbers that are then recorded digitally like any other data. The recovery of the signal consists of reading back the series of numbers (again, at precise time intervals), converting them into values of an analog quantity (e.g., voltage), and smoothing these discrete values into a waveform.

The first design consideration of a digital recorder is the frequency of sampling, which must be at least twice the highest frequency present in the signal to be recorded, according to the Nyquist theorem. Thus, for a high-fidelity audio

signal containing frequencies up to a 20 kHz, sampling might be done at a rate between 40,000 and 50,000 times per second. Next, the dynamic range of the final reproduction is determined by the precision of each conversion to digital form. If a final dynamic range of 60 dB (an amplitude ratio of 1000) is required, then the binary code for each sampling must be able to express integer numbers from 0 to 1000. This requires ten bits per sampled value, since $2^{10} = 1024$. Similarly, a dynamic range of 90 dB requires a minimum of 15 bits per sampled value. The dynamic range is essentially the signal-to-noise ratio of the reconstructed signal, since the steps between adjacent numerical values provide the only noise inherent in the final output.

The advantages of a properly designed digital system include an excellent dynamic range, an essentially perfect time-base (absence of "wow" and "flutter"), and the ability to do repeated editing or dubbing operations without signal degradation. The tenth-generation audio reproduction made on a studio digital recorder is virtually indistinguishable from the original. This resistance to degradation of the recorded signal is intrinsic to digital technology and results from the fact that the information is encoded only in the timing of transitions. As long as these can be reliably detected and are not shifted, substantial degradation of the amplitude or shape of the digital waveform can occur with no effect on the result.

Digital magnetic recording, while not requiring linear reproduction of a waveform, makes great demands upon the recording system because of the drastically increased bandwidth. If an audio signal of 20 kHz bandwidth is to be reproduced with the modest dynamic range of 60 dB, frequencies up to at least 225 kHz are needed to accomodate its digitally encoded representation. An actual studio recorder might operate beyond 600 kHz, depending upon sampling rate, dynamic range, and the digital code used. Such frequencies dictate very short intervals between the magnetic transitions on the recording surface if tape usage is not to become prohibitive. On the other hand, the signal-to-noise ratio of the digital waveform that is read back need not be as great as that required in an analog recording. In general, the lower the signal-to-noise ratio of the digital waveform the higher the probability of mis-read bits (bit errors), but these can be detected and either corrected or concealed through the use of encoding schemes that involve a certain amount of redundancy in the recorded information. These schemes can overcome not only isolated single-bit errors but also the effects of recording surface defects that delete a number of adjacent bits. (See, for example, reference 6).

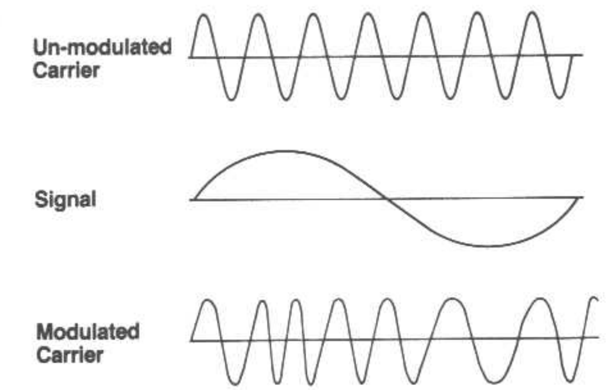
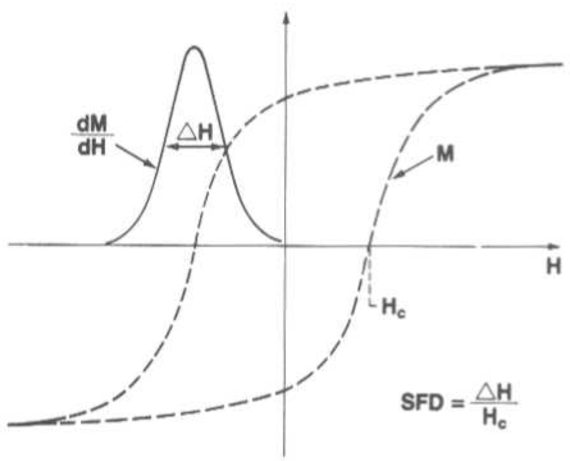


Fig. 7. The principle of frequency modulation (FM).

Error correction techniques make possible the use of very high densities in digital recording, provided that the heads and media can operate with the required resolution.

Another mode of magnetic recording that does not require linear waveform reproduction is frequency-modulation (FM). This is primarily used in video recording[7], but can also be applied to audio recording and is in fact used to give high-fidelity sound in some video cassette recorders. The principle of FM is that a carrier wave is generated whose *frequency* varies with the *value* of the signal to be transmitted (Fig. 7). It is this frequency-modulated carrier that is recorded on the magnetic medium. As in digital recording, the information is contained in the intervals between the zero-crossings of the recorded waveform; its amplitude is not significant as long as the signal-to-noise ratio is adequate for reliable detection. Unlike digital recording, FM recording contains an analog relationship between frequency and the value being transmitted. The benefits of FM, as compared to direct analog recording, are twofold. One is the insensitivity to amplitude variations in the recorded waveform. The second, which is crucial to magnetic video recording, is that FM reduces the ratio of the highest to the lowest frequencies that need to be recorded; this is shown schematically in Fig. 8. Suppose that it is desired to record a video luminance (brightness) signal that contains frequencies from 30 Hz to 4.5 MHz. The upper and lower frequency limits have a ratio of 150,000 or 17 octaves. (By comparison, a full-fidelity audio system is required only to reproduce frequencies from 20 Hz to 20 kHz, a ratio of 1000, or 10 octaves.) A frequency span of 17 octaves (ratio of 150,000) is impractical in magnetic recording. First, the ratio of highest to lowest frequencies cannot exceed the ratio of the physical length of the playback head pole-pieces to that of the gap (reference 1, pp. 99-119). This ratio cannot in practice be as great



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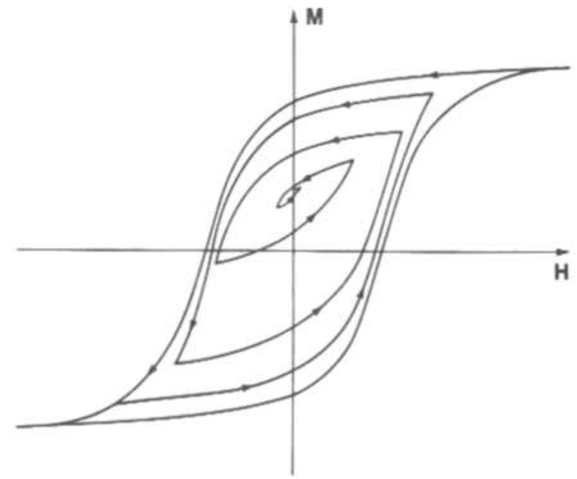

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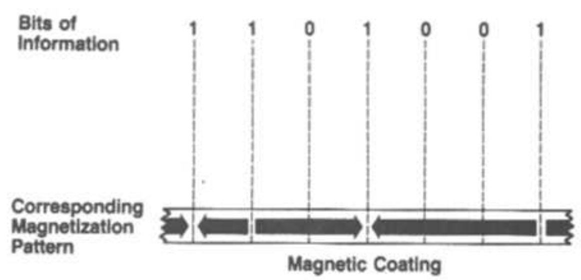

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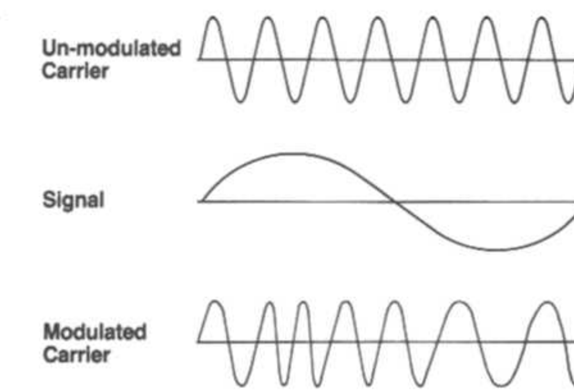

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The frequencies involved in video reproduction are much higher than those in audio. Since there are practical lower limits on the recorded wavelength, this means that much higher head-to-tape speeds are needed. To attain these speeds, all video systems use heads mounted on a spinning drum. The tape is transported around part of this drum at a speed much lower than that at which the heads are moving across the tape surface. The various systems in current use employ different FM carrier frequencies as well as different schemes for conveying the color information, which in practice has a lower resolution and therefore requires a smaller bandwidth than that of the luminance information. In all systems the hue and saturation information is conveyed by amplitude and phase modulation of a special color sub-carrier (at 3.58 MHz in the U.S.A.). In the one-inch, open-reel tape format commonly used in broadcasting, the modulated color sub-carrier is simply added to the luminance signal and the resulting sum is the signal used to

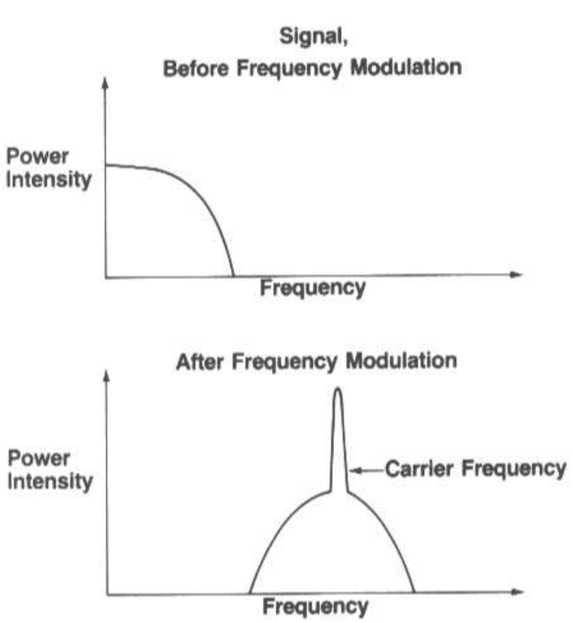

Fig. 8. In frequency-modulation (FM) the information is shifted to higher frequencies, but the ratio between highest and lowest frequencies is greatly reduced. FM schemes actually used in video recording do not use all of the sideband frequencies; see pp. 396-401 of reference 2.

frequency-modulate the video carrier. In 3/4-inch U-matic systems and in non-professional one-half-inch cassette systems, the color sub-carrier (with its amplitude and phase information) is heterodyned down to a lower frequency (about 0.6 MHz) which is then recorded directly, using the frequency-modulated luminance carrier for ac-bias. Some recently developed one-half-inch cassette systems for professional applications utilize FM recording of both luminance and color information with a separate head, tape track, and carrier frequency for each. This achieves broadcast-quality reproduction using the same cassettes used in consumer systems, but at the cost of much lower recording densities (higher tape consumption).

MAGNETIC RECORDING MEDIA

Most magnetic recording media in use today are made by dispersing small magnetic particles in an organic binder and coating the resulting "paint" on a support material. See Fig. 9A. Each particle remains uniformly magnetized; its magnetization can change its direction but not its magnitude (this is a result of the very small size). The particles are sufficiently small that there are many of them in each magnetized region of the recorded pattern; this provides the needed resolution and signal-to-noise ratio. The particles can be of various types, according to the intended application[8,9]. In addition to the magnetic particles, the coating contains polymers for strength, lubricants to reduce friction and wear, and surfactants to aid in dispersing the particles. An additional particulate component is usually added to impart a controlled amount of abrasivity for head-cleaning purposes.

Another possible construction for a magnetic recording medium is shown in Fig. 9B. Like the dispersion-coated type, it also uses a non-magnetic base. The magnetic substance is in the form of a thin metallic film. Thin films offer magnetization intensities far surpassing those available in the coatings of dispersed particles, which compensates for the films' much lesser thickness. The thinness of the films is in itself an advantage in that the magnetic material is all in very close proximity to the record or playback head. This intimate contact with the head is extremely important to high-density recording and is further enhanced by the great smoothness possible in the thin films. These attractive features make thin-film recording media an exciting area of research and development and possible candidates for future products. At present, their major commercial applications are in video instant-replay memories and in advanced computer disks.

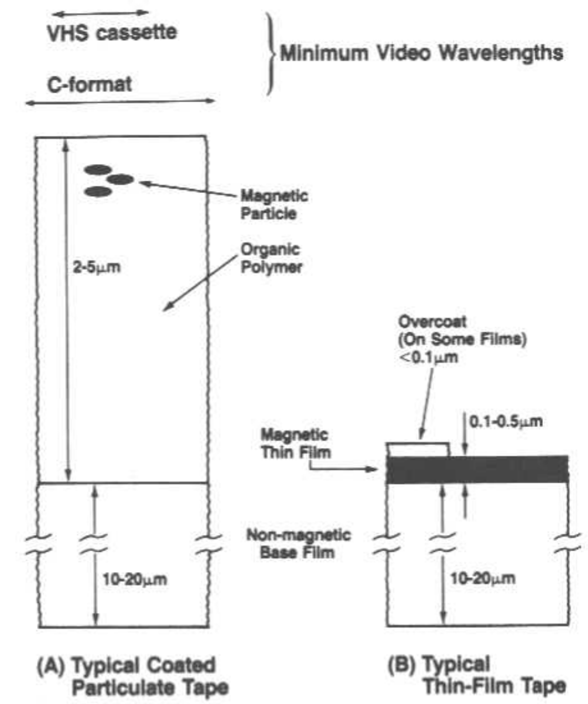

Fig. 9. Cross sections of a coated particulate recording tape and a thin-film tape. The particles are drawn approximately to scale but their spacing and uniformity have been exaggerated. Only a few have been drawn, although they actually fill the magnetic coating layer, occupying about 40% of its volume.

On the negative side, metallic thin films are subject to some concerns regarding their chemical stability, durability, and economical manufacture. Many of them are coated with a thin non-magnetic overlayer for protection and lubrication. This layer, of course, tends to diminish the closeness of contact with the head. Metallic thin films are made by chemical plating or by some form of vacuum deposition and usually contain cobalt as a major constituent. The need for the special equipment used to carry out these processes is an additional barrier to the widespread commercial use of thin films in recording media. Futhermore, the thin-film products must compete with a particulate technology that not only benefits from more than 30 years of experience in manufacturing and application but is also evolving toward greater capability.

For the foreseeable future, economic and practical considerations dictate that coatings of dispersed particles will be predominant in audio and video tapes. The earliest comercially available audio tapes, made in the late 1940's, used iron oxide particles. The most important oxide, $\gamma-Fe_2O_3$, has been greatly improved as to particle shape and size since its introduction, and it retains an important role in audio, video and data-recording tapes today. It is also the most commonly used material for the disks, both flexible and rigid, used in digital data storage for computers. The relatively low coercivities (250-400 Oe) of pure iron oxides, however, proved to be a serious limitation as recording densities increased. An explanation for this is found in the self-demagnetization effect that exists in magnetized materials. Every magnet generates an internal field, which tends to oppose the magnetization that gives rise to it. This effect becomes stronger as the magnet is made shorter along its direction of magnetization (Fig. 10), and will be enhanced by the presence of nearby magnets if similar poles are placed together. The result of these phenomena is that magnetic recording, conventionally visualized as having the magnetization parallel or antiparallel to the direction of motion of the head with respect to the tape or disk (Fig. 1), suffers from a demagnetization effect that becomes more severe as the recording density becomes higher (that is, as the recorded wavelength becomes shorter). The ability of a magnetic material to resist demagnetization is expressed by its coercivity.

The requirement for higher coercivities was first met in the mid-1960's with the introduction of chromium dioxide (CrO_2). Like iron oxide, this material derives its coercivity and squareness properties, and therefore its ability to retain magnetization, from the needle-like shape of the particles. Chromium dioxide was first introduced for digital computer tapes. It was soon applied in audio cassettes and is today used in some video cassettes.

At the present time, the most widely used materials for applications requiring coercivities in excess of 400 Oe are iron oxide particles modified by the addition of cobalt. The interaction of the cobalt ions with the iron oxide structure provides additional resistance to the switching of the magnetization direction, and thus increases the coercivity. Values in the range of 500-600 Oe for audio cassette tapes, 600-700 Oe

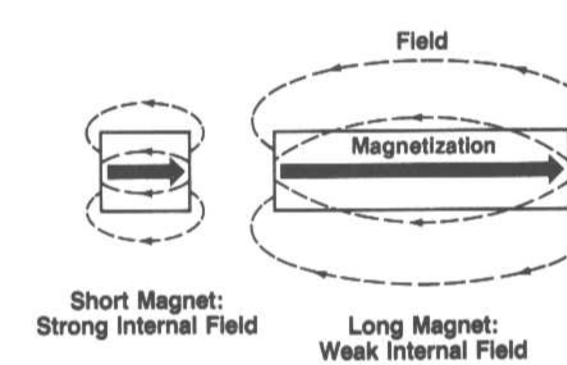

Fig. 10. Internal demagnetization fields for magnets of different shapes.

for video tapes, and 800 Oe or above for future applications are readily achieved. Many processes exist for adding the cobalt to the particles. Most in use today leave the cobalt segregated near the surface of the particles. Such particles, called "cobalt-surface-doped", "cobalt-adsorbed", "cobalt-epitaxial", or "cobalt-ferrite epitaxial" are now the predominant materials used in video cassettes and open-reel video tapes and are finding increased use in high-density data diskettes. Like undoped oxides and chromium dioxide, they retain magnetization along the particle axis. The manufacturing processes of tapes are usually designed to orient the particles along the tape length in order to increase the maximum remanent magnetization in this direction.

Tapes made with particles of metal (iron or iron alloys) have much higher remanent magnetization values than are possible in tapes that use oxide particles, and accordingly give much higher signal levels. This property is especially valuable in very compact formats, and metal particles are used in some audio cassette tapes and also in 8-mm consumer video tapes. These products have generally had coercivity values in excess of 1000 Oe, requiring much higher head fields for recording and erasure than those needed for oxide tapes. Recently, however, metal particles have become available with coercivities near 700 Oe, similar to those of cobalt-modified oxides.

Another particulate material currently being studied for recording applications is barium ferrite. The particles are formed in the shape of small hexagonal plates, each of which has its easiest axis of magnetization perpendicular to its flat faces. If these plates are incorporated into a tape coating so as to lie roughly in the plane of the tape surface, recording can be done primarily with perpendicular magnetization.

Fig. 11 shows the properties of various particulate magnetic recording materials.

Whatever the composition of the particles in a recording tape or disk, their size is extremely important, since it determines the number of particles contained in each magnetized region of the recorded signal. The greater this number, the greater will be the maximum signal-to-noise ratio that the recording medium can provide, since each particle contributes a pulse of magnetization to the playback head[10]. A great many small pulses clearly will combine to make a more accurate, less noisy signal than a smaller number of large pulses (even though the total density of magnetic material present may be the same), and the effect of random fluctuations in particle size or placement will be less.

One of the most important and difficult arts in the manufacture of magnetic recording media is the dispersion of particles in the coating. If appreciable amounts of the particles are clumped together, the recording performance will suffer. The noise properties of the signal will be dominated to some extent by the clusters of particles, which are of course much larger than the individual particles themselves. A great deal of attention must therefore be paid to the formulation and milling of the dispersion, and to its coating and drying.

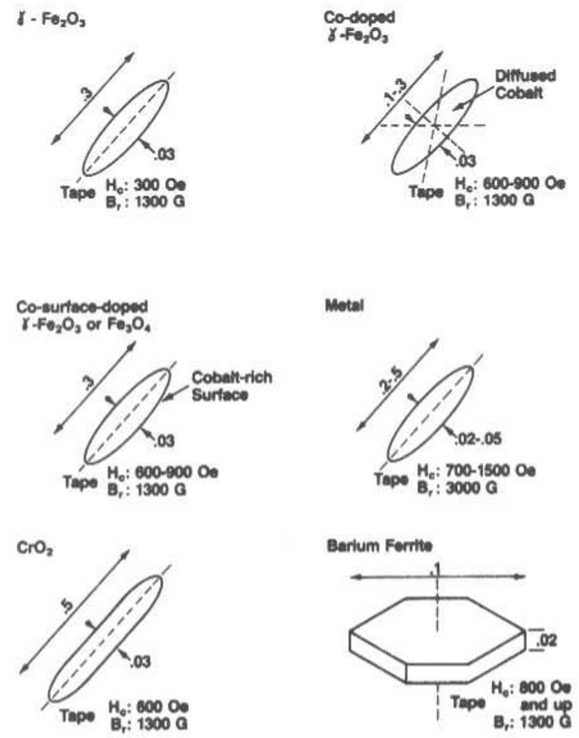

Fig. 11. Various particles used in magnetic recording. The preferred axes of magnetization are shown by broken lines. Some typical, approximate dimensions (in μm) and magnetic parameters are indicated.

In the search for magnetic materials that give higher performance, care must be taken to avoid various undesirable features. For example, the trend to reduce particle size, and thus enhance signal-to-noise ratios, must not be carried to the point where the particles are so small that they begin to show the effects of thermal instability. In particular, the presence of excessively small particles can lead to the unwanted acquiring of a signal in one layer of tape on a reel as a result of the fields due to a strong signal on an adjacent layer. This phenomenon is often referred to as "print-through" or "pre- and post-echo", and is important only in (ac-bias) audio recording. In some applications, especially audio, thorough erasure is an important concern and one that places an upper limit on the coercivity of the recording medium. Efficient recording and erasure also require that the material's switching-field distribution (Fig. 4) be relatively narrow. This means that the fields required to reverse the magnetization of the individual particles should be tightly clustered around the coercivity (which is essentially the median switching field).

Although this discussion has focussed on magnetic properties, one must not underestimate the importance of the non-magnetic components of recording media. The base film, the binder polymer, and the various lubricants and other additives in the coating are crucial to strength, durability, and freedom from undesirable levels of friction. The manufacture of recording media requires at least as much capability in organic chemistry as in magnetic materials. The ability to reliably produce coatings with smooth surfaces, substantially free of defects, is also an absolute necessity.

PROGRESS TOWARD HIGHER RECORDING DENSITIES

The state of the art in magnetic recording has clearly advanced in recent years. Fig. 12 shows the great gains in practical recording density that have occurred in the video area. Intensive research and development is today aimed at continuing this trend. Two major driving forces are the desire for more compact consumer video products, especially cameras, and the trend toward digital recording of both audio and video signals. A brief survey of current developments will be given here, with emphasis on digital video.

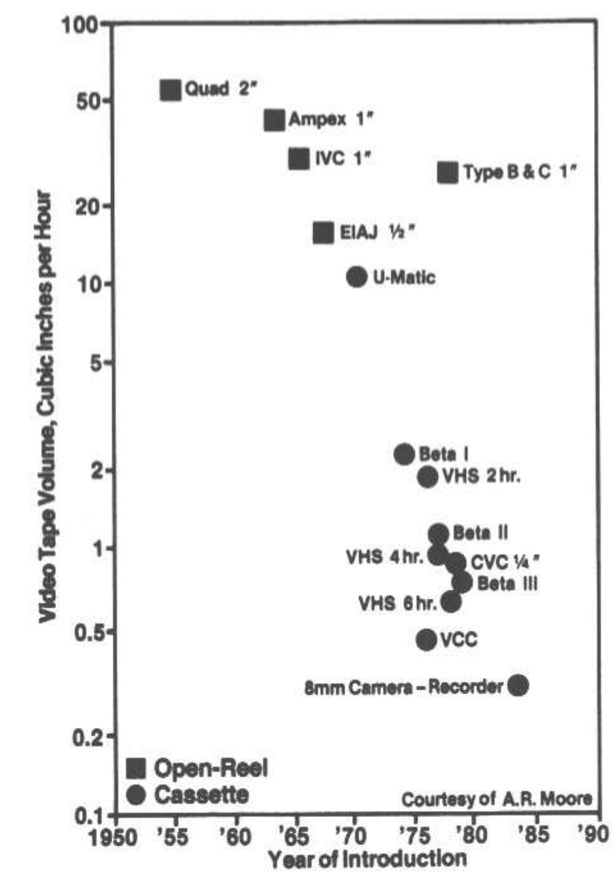

Fig. 12. Tape volume required per hour of playback, plotted against year of introduction, for various video formats. This plot was supplied by A.R. Moore, of 3M.

As was mentioned earlier, the use of digital techniques requires a frequency bandwidth that is much increased over that needed for analog representation. Consider, for example, a broadcast-quality video signal that requires a bandwidth of roughly 10 MHz for adequate analog (FM) transmission. The analog recording system must handle 2×10^7 magnetic transitions per second. A digital system designed to transmit this same signal adequately would require nearly 3×10^8 bits per second[5]. Assuming that one bit of information corresponds to one magnetic transition (although this ratio varies somewhat with the digital code used), the digital recording system must handle nearly 3×10^8 magnetic transitions per second, a fifteen-fold increase over the analog rate. Clearly, if the use of digital rather than analog technology is not to entail a large increase in tape consumption, the digital recorder must use a higher density of magnetic transitions per square inch of tape. This density is the product of track density and the linear transition density along a track. Table I gives the values of these parameters in some practical and hypothetical video systems. The projected increases of recording density require the achievement of adequate signal strength and signal-to-noise ratios despite the use of much smaller magnetized regions in the recording medium. The difficulty presented by self-demagnetization at high densities was described earlier, as an explanation for the need to increase coercivities. However, a limit exists as to how much high-density performance can be bought by simply increasing the coercivity, since available heads must still be able to record, and also to erase or over-write, the material. Another route to avoiding or relaxing the density restrictions imposed by demagnetization is to avoid the head-to-head arrangement of magnetized regions. This can be done by using, to a greater or lesser extent, the perpendicular (sometimes called vertical) component of magnetization[11,12]. See Fig. 13. The relative merits of the various recording patterns, and of various head designs for creating and reading them, are currently under intensive study in many academic and industrial laboratories. It is likely that recording at relatively high densities has always used some degree of perpendicular magnetization, but new materials, including barium ferrite particles and some metallic thin films, are designed to accentuate this com-

TABLE I

System	Current C-format, one-inch open-reel video	Current six-hour VHS video	Projected digital video[a]
Magnetic Transitions per second (maximum)	2×10^7	10^7	3×10^8
Transitions per inch along track (maximum)	2×10^4	4×10^4	10^5
Tracks per inch	1.4×10^2	1.3×10^3	10^3
Transitions per square inch (maximum)	3×10^6	5×10^7	10^8
Tape consumption, in square inches per second	10[b]	0.2[b]	3

[a]This system embodies recording densities achieved in the laboratory. Digital systems closer to practical realization use somewhat smaller densities and achieve a tape usage closer to that of the analog C-format.[5]

[b]Includes tape area not devoted to video information.

ponent. The multiaxial cobalt-doped oxide particles (see Fig. 11) can be used to implement mixed-mode recording (Fig. 13) in a more or less isotropic medium.

Output losses at high densities can result from a number of causes other than demagnetization. Some are related to head design, and it is very clear that development of heads and recording media must proceed together in the search for higher-density recording. Fig. 14 shows some head designs under current consideration. The critical dimension of the head used for playback, the gap width of a conventional ring head or the pole width of a perpendicular-recording head, must be smaller than the shortest wavelength to be reproduced. The head used to record the waveform can have larger dimensions; indeed, this may be advantageous.

Whatever the head design and the recording medium composition, the closeness of the contact between the head and the surface of the medium is a factor of major importance in determining the achievable recording density. This

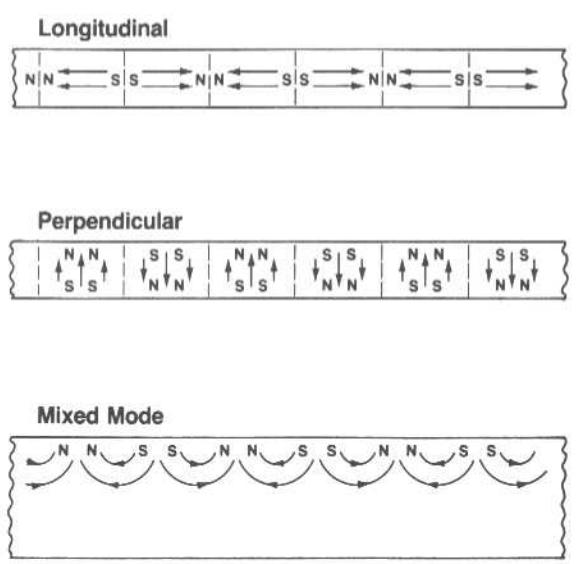

Fig. 13. Possible magnetization patterns in recording media. For the perpendicular component, increasing the recording density may actually decrease the demagnetization fields; see Fig. 10.

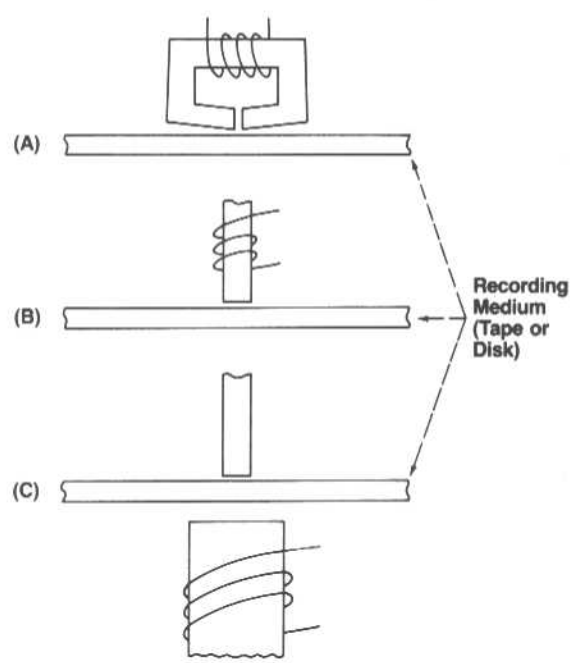

Fig. 14. (A) Conventional ring-type head, useful for both longitudinal and perpendicular recording. (B) Single-pole head, for perpendicular recording. (C) Single-pole head, driven by auxiliary pole, for perpendicular recording[11]. All heads can, if made with suitable dimensions, be used for reading as well as for writing. (B) and (C) are largely in the research and development stages at present.

follows from the fact that the resolution with which the head can record and read back deteriorates rapidly as spacing increases. The effect on the recording process has been estimated as a loss of 44 dB per wavelength of spacing, for a sinusoidal signal[13], and that on the playback process as a loss of 55 dB per wavelength[14]. This total of nearly 100 dB per wavelength means, for instance, that for sinusoidal recording at 50,000 transitions per inch (corresponding to a wavelength of 40 microinches or about one micrometer) every microinch of spacing will cause about 2.5 dB of overall loss in the reproduced signal. Obviously, variations in the spacing will amplitude-modulate the signal with the same sensitivity, and therefore add noise components to the signal. Thus, media surface smoothness may well be the ultimate limiting factor of magnetic recording density, although further development of heads and media are needed in order to reach this limit[15]. In addition to smoothness, the freedom from flaws and contaminants is crucial, if information "drop-outs", or momentary losses of signal, are to be minimized. As mentioned earlier, techniques of error detection and correction (or concealment) allow satisfactory performance even if imperfections exist in the recording medium. Even a highly sophisticated error-correction system, however, can be overwhelmed by defects that are excessive in number or size. As the recording density increases, the size of the flaw needed to cause a given system failure (visible video defect, audible audio defect) decreases. Thus, the development of advanced magnetic recording media entails the search for the means of producing highly perfect surfaces, as well as ideal magnetic properties.

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