Magnetic Recording Heads; Theory and Practice

Fred Jeffers

Kodak Research Laboratories

San Diego, California

> 50kfci

High Density Recording Heads

- Important dimensions and parameters and why they are important
  ("contact" recording only - special problems of flying heads will not be discussed)

physics, not math!

Outline

Gaussian Units

- Head-to-media spacing
- Record gap size
- Media coercivity H_c and remanence $4\pi M_r$
- Record demagnetization and "demag" fields
- Record saturation
- Thin film heads
- Head wear
- Gap edge straightness & gap length uniformity
- Magnetoresistive heads
- Vertical recording and pole heads
- Head noise

INTRODUCTION

The trend in magnetic recording development is toward ever higher areal storage density; that is, more tracks per inch of medium width and higher linear density. The increase in linear density, now approaching 100,000 flux changes per inch, 100 kFCI, has been accomplished by dramatic increases in media coercivity and reduction in head gaps and head-to-media separation. The advent of digital audio, higher video frequencies, and higher digital data rates also requires higher head-to-media speeds which increases wear and reduces head life. A density of 100 kFCI requires a head gap length < 1000 atomic layers and a head-to-media separation < 100 atomic layers! The situation has now progressed to the point that further improvement in high-density recording system performance is mainly limited by the magnetic materials and fabrication processes used to construct the heads.

In order to achieve good high-density performance, the heads and media must be in intimate contact. Even a separation as small as $\lambda/10$, where $\lambda = 2 \times$ bit length, results in a signal loss of 10 dB or a factor of 3. This requirement is especially difficult for thin film and ferrite/metal composite, metal-in-gap (MIG), heads which suffer from pole tip erosion because of differential wear.

In rigid disk systems, the heads fly over the media and the intimate head-medium contact required for high-density recording is ruled out. This paper is concerned with high-density recording heads; discussion will be restricted to heads for flexible media, such as floppy disks and tape, where intimate head-medium contact can be achieved. Many aspects of the subject are common to both types of heads, but the special problems associated with flying heads will not be discussed.

The record gap must be as small as possible to increase the record field gradient at the surface of the medium, but gap corner saturation must be avoided. Current metal particle tapes for 8 mm video have coercivities a factor of two higher than the maximum of 625 Oe that can be optimally recorded by conventional ferrite heads. In thin film heads, yoke saturation must be avoided which makes the heads hard to build and limits head life.

When the wavelength approaches the reproduce gap length, the signal goes to zero. This is called "gap null loss" and the reproduce gap must be very small to retain adequate high-density signal. The head material must have high permeability and low wear to give adequate signal with a gap depth providing acceptable head life. Gap edges must be as straight and parallel as possible. Thin-film head materials must have high permeability and zero magnetostriction, in addition to high saturation flux density.

Vertical recording media give improved high-density performance because the associated demagnetization fields aid the record fields, rather than oppose them as in conventional media. Vertical pole heads work well recording on vertical media equipped with a high permeability underlayer, but not in reproduce, because of a trade off in gap null loss, and record and reproduce efficiency. Ring-type heads give superior reproduce performance with vertical media. The highest linear density of 230 kFCI has been achieved using unkeepered vertical CoCr media and very small gap ring heads.

Magnetoresistive, MR, reproduce heads provide much higher signal levels than inductive heads. An inductive head would need 4000 turns to provide the same 100 kFCI signal as an unshielded MR head at a media speed of 1 inch/sec. At 10 kFCI, it would need 100,000 turns! Since MR head signal is independent of media speed, the signal advantage decreases as media speed increases, but there is a maximum inductive head speed determined by self-resonance effects. In general, MR head signal is larger than that for real inductive heads at any practical media speed or linear density.

The goal in a properly designed reproduce system is to make the sum of the various head noises smaller than the magnetic noise from the media. Primary inductive head system noise sources are resistance noise of the head, amplifier current noise (which varies with net head impedance) and amplifier voltage noise. Both resistance and current noise increase with frequency. High-density inductive reproduce heads can achieve media-noise-limited performance, but the margin between media noise and head noise is seldom more than 4 or 5 dB even for wide, 10 mil, trackwidths.

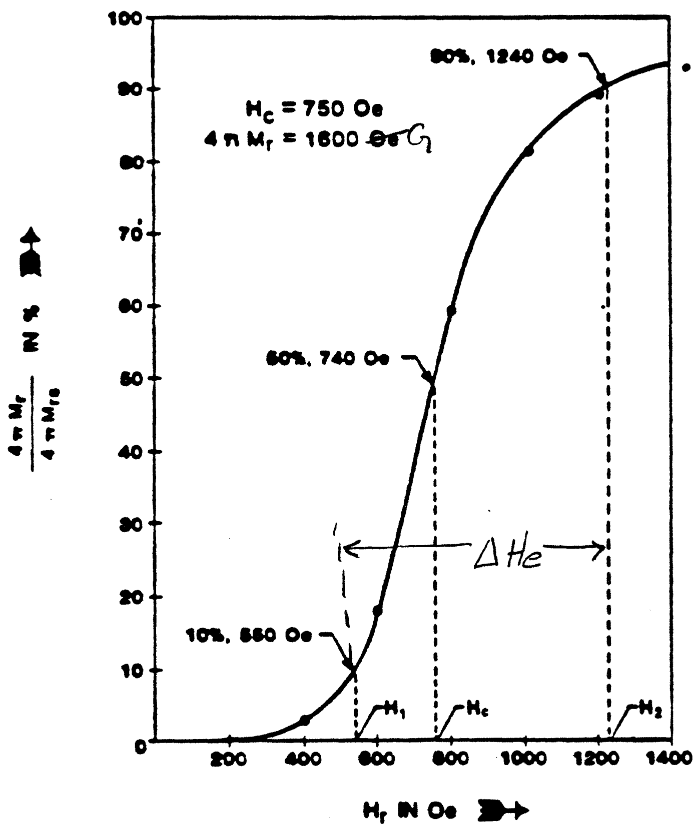
The most important MR head noises are scrape thermal noise, caused by hard media asperities being dragged over the head surface, and Barkhausen noise, due to abrupt motion of domain walls in the MR sensor. MR heads are nonlinear devices and must be biased into a linear zone. Waveform distortion from improper biasing and MR element saturation can be a problem. MR heads can achieve media-noise-limited performance at areal densities as high as 200 MFC/in^2. This is much higher than can be achieved with inductive reproduce heads and is comparable to optical recording storage density.

DISCUSSION

Recording Process

If a signal field H_r is applied and removed, neglecting demagnetization fields, the medium is magnetized according to the curve sketched in Fig. 1, where $4\pi Mr$ is the remanence and $4\pi Mrs$ is the saturation remanence.

FIG. 1 REMANENCE VERSUS RECORD FIELD



H_1 and H_2 define the boundaries of the record field range and the 50% field is generally close to the media coercivity Hc.

Standard record head and record field contours are shown in cross-section in Fig. 2. The cross-hatched regions is where recording takes place and is called the record zone. The "depth of recording" Y_m is the height of the $H = H_c$ contour. L is the "record zone length".

FIG. 2a MAGNETIC HEAD

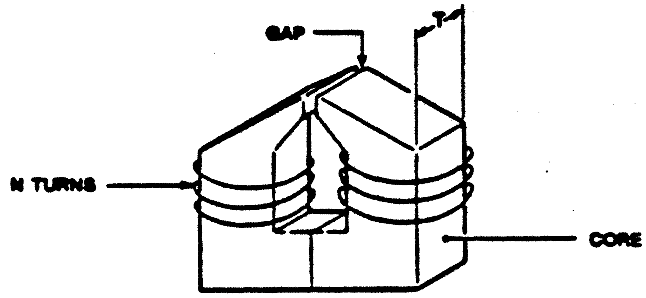
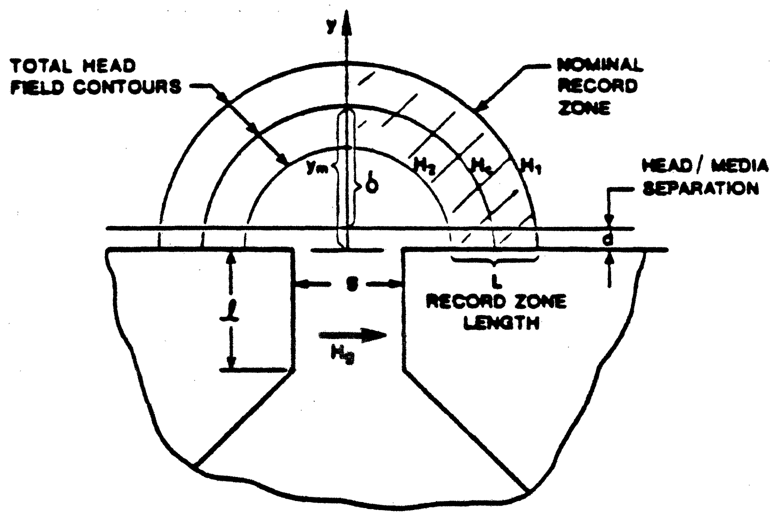


FIG. 2b CROSSECTION OF RECORD GAP & HEAD FIELD CONTOURS



The gap field H_g is related to the record current i_r and the number of turns on the record head N by the expression

$$H_g = E\frac{4\pi N i_r}{10g} \tag{1}$$

H_g in Oe N=TURNS
i_r in amp.
g in cm.

where E is the head efficiency. E represents that fraction of the magneto-motive force Ni_r that appears across the gap. (It is also the fraction of the tape flux passing through the coils during reproduce.) McKnight[1] gives a good review of detailed efficiency calculations for standard heads. Neglecting "air leakage", E is given approximately by

$$E = \frac{R_g}{R_g + R_c} \quad \text{= EFFICIENCY} \tag{2}$$

where R_g is the gap reluctance given by

$$R_g = \frac{g}{T\ell} \tag{3}$$

where g is the gap length, T is the track width, and ℓ is the gap depth. The core reluctance R_c is given by

$$R_c = \frac{c}{\mu \bar{A}} \tag{4}$$

where μ is the core permeability and C is the circumference of the core. A represents the "average cross-sectional area" of the core. The fabrication process must not reduce the permeability of the head-core material by inducing strain. A reduction factor of 5 is not uncommon.

It will be shown later that in high-density recording, nearly all of the reproduce signal comes from the surface of the medium. Using λ = wavelength = 2 x bit length, 90% of the signal comes from the top λ/e of the recording layer. At 100 kFCI, $\lambda = 0.5\mu m$, so $\lambda/e = 0.18\mu m$. In a particulate medium, only the top layer of particles is recorded at high density. The rest of the layer only smooths out roughness in the substrate surface.

At high density, when the bit length approaches half the record zone length L/2, the high Hc fraction of the particles in the medium are recorded "positive" and the low Hc fraction are recorded "negative" as sketched in Fig. 3.

NiZn FERRITE HEAD
SURFACE DEAD
LAYER
$\simeq 4\mu''$
MnZn $\lesssim 1\mu''$

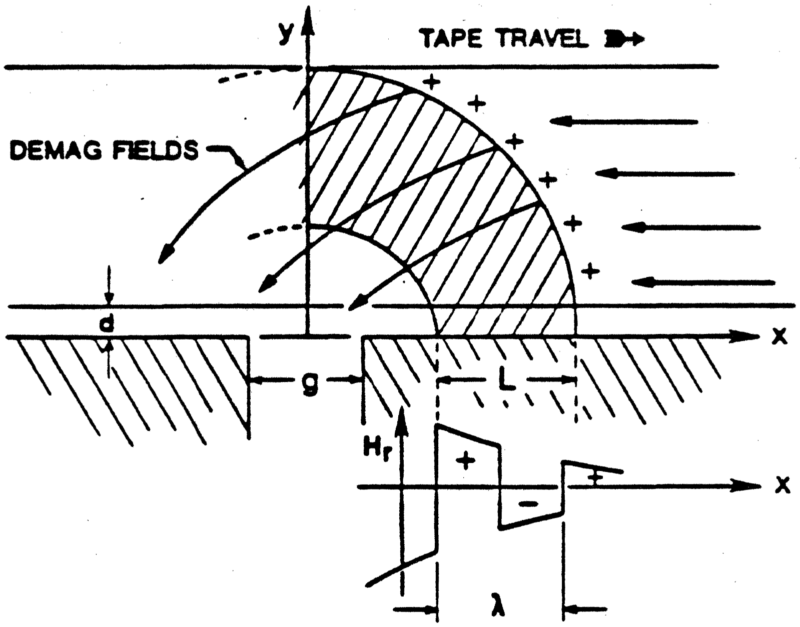


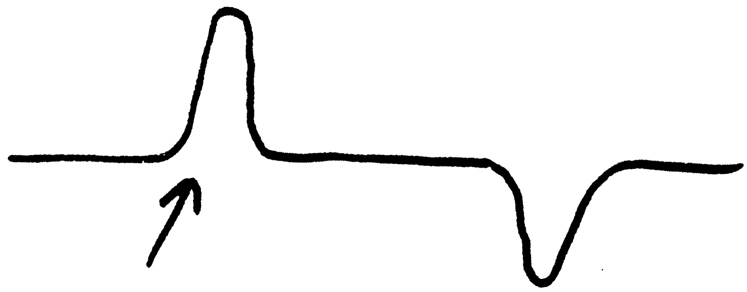
FIG. 3 High density record field versus distance compared to a long record zone length.

This results in cancellation; hence, a low recorded signal. This is called subsequent cycle erasure, or recording demagnetization.

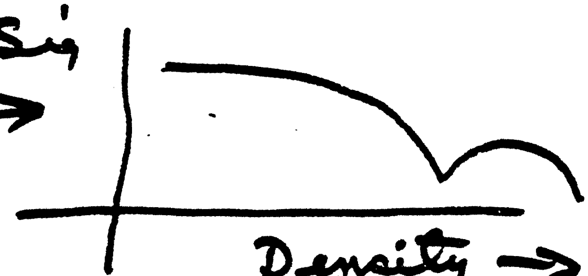
When the head-tape separation d increases, L, at the surface of the medium, increases giving more erasure at high density. Bertram[2] has shown that for standard high density media having $4\pi M_{rs}/H_c$ ratios ≈ 3, the record separation loss is given by $-44\ d/\lambda$ dB, where λ is the fundamental wavelength or twice the bit length. This expression is a conservative estimate of the loss caused by a momentary loss of contact such as that due to a speck of dirt on the medium because, in Bertram's experiment, the record current was increased to partially compensate for the loss of contact. If H_c is increased, this loss factor becomes smaller because the record fields then become larger relative to the demag fields and less recording demagnetization occurs.

The reproduce separation loss is the familiar[3] $-55\ d/\lambda$ dB, so the net separation loss is - $-99\ d/\lambda$ dB. If d is $\lambda/10$, the signal loss is 9.9 dB or about a factor of 3. If the recording density is 100 kFCI, $\lambda/10 = 0.05\mu m$ or only about 250 atomic layers! The importance of good head-to-media contact cannot be overemphasized!

Under "proper" record cond.
"Recording Demagnetization" is <u>small</u>



Superimposed isolated pulses will generate



"proper" ≡ small gap heads and record current set to <u>peak</u> very short $\lambda \leq 0.75\,\mu m$ signal.

Fig 3a

Hc

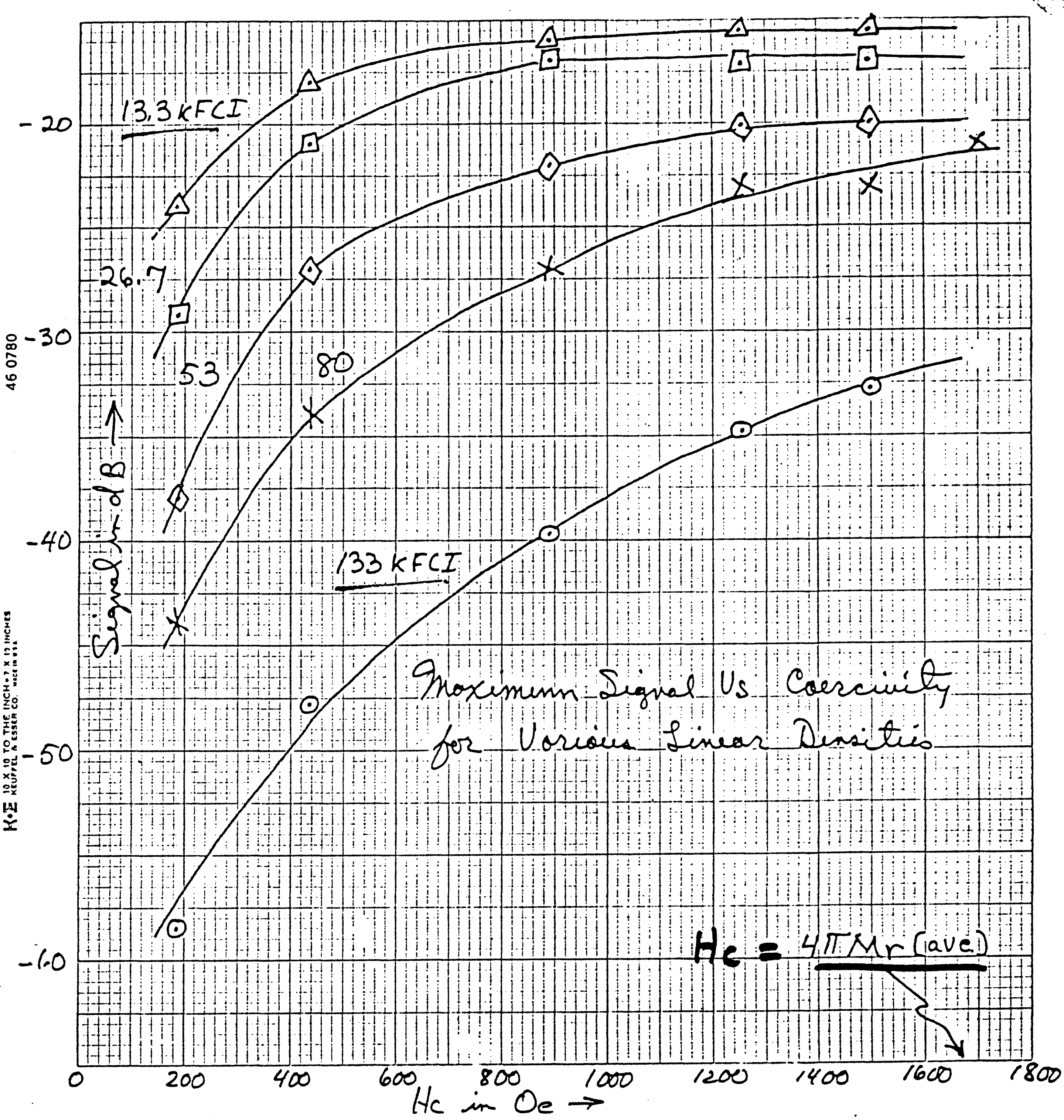
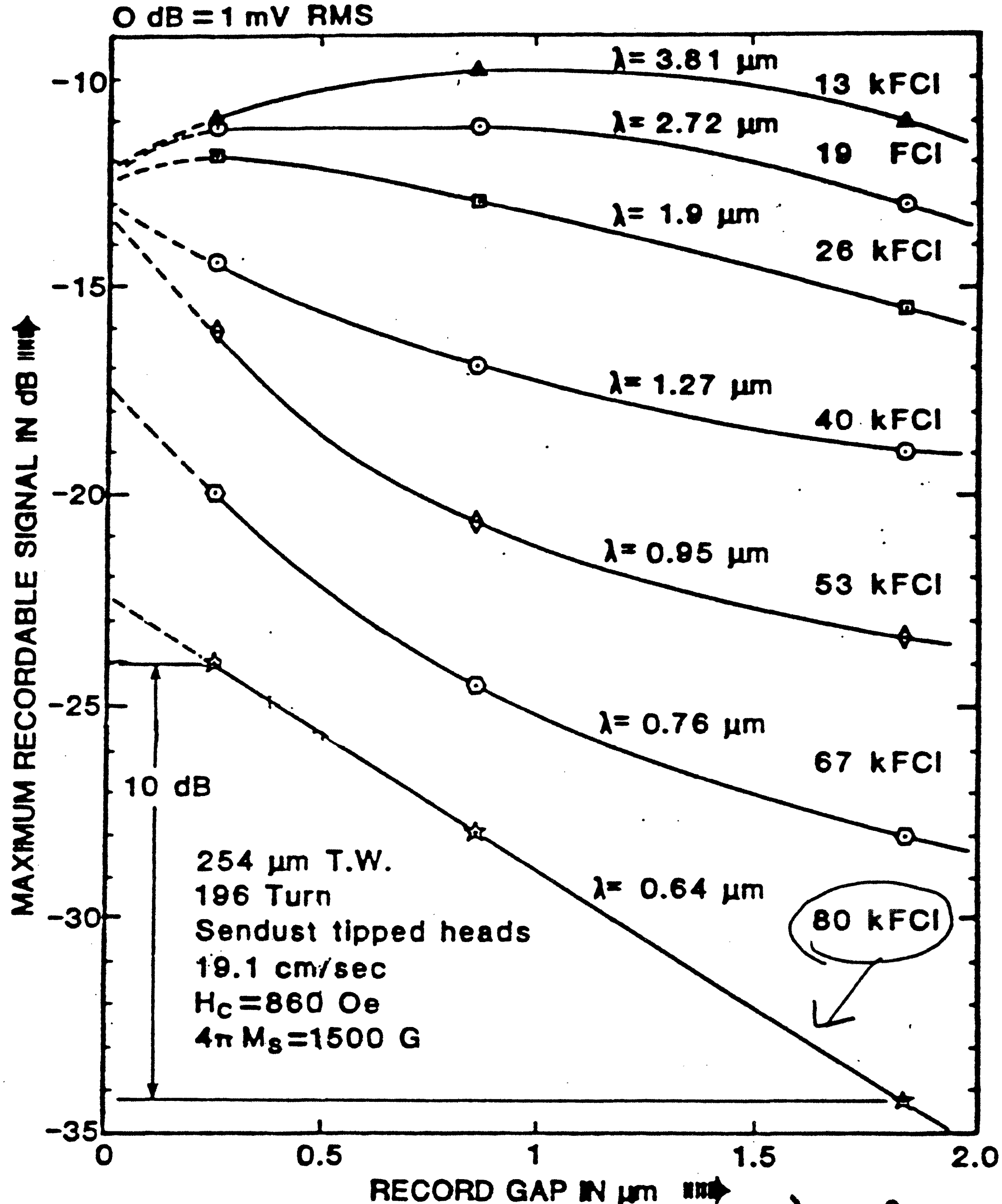


Fig. 36.

For **This** surface Smoothness!

Increasing Hc increases high density signal, however this requires higher gap field.

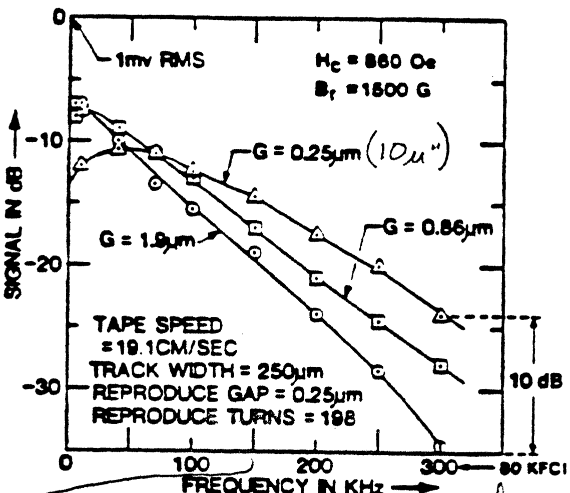


Reducing g increases high density signal,

Fig. 4a Maximum recordable signal versus record gap for various wavelengths.

--- However smaller g ⇒ higher gap fields & more saturation at gap corners.

The standard approach to achieving a narrow record zone is to use a small record gap. It has been shown that for any wavelength less than the medium thickness, when the head and medium are in good contact, the maximum recordable signal increases as the record gap is reduced, and it reaches a maximum when saturation occurs at the gap corners.* Figure 4 shows the maximum unbiased RMS signal versus frequency at a constant tape speed of 19.1 cm/sec for 3 metal-tipped record heads having gap lengths of 1.9µm, 0.86µm, and 0.25µm. The heads have ferrite cores and "glued on" Sendust pole tips as sketched in Fig. 5. The same reproduce head having a gap of 0.25µm was used for each curve. The media was an acicular Co-doped γFe_2O_3 tape with $4\pi Mrs \cong 1500$ G and H ≅ 860 Oe. The record current was optimized at each frequency. The highest frequency of 300 kHz corresponds to 80 kFCI digital density. The very small 0.25µm gap head records 10 dB, or a factor of 3, more 80 kFCI signal than does the 1.9µm gap head.



40 kfcI

Ir adjusted to peak each freq

FIG. 4 Record performance of three different Sendust tipped record heads gaps.

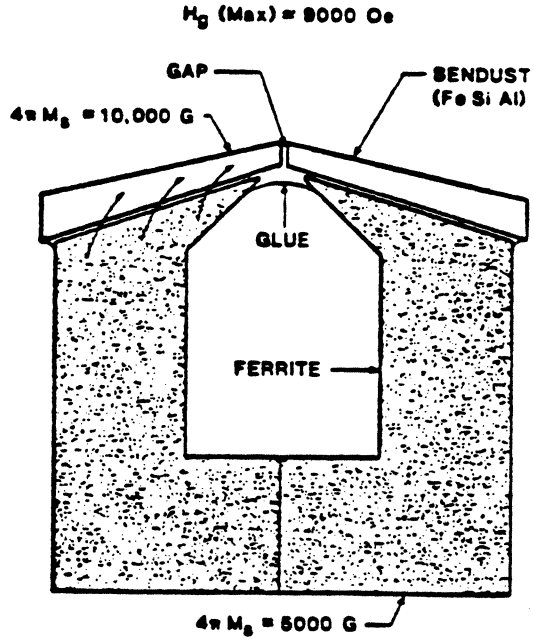
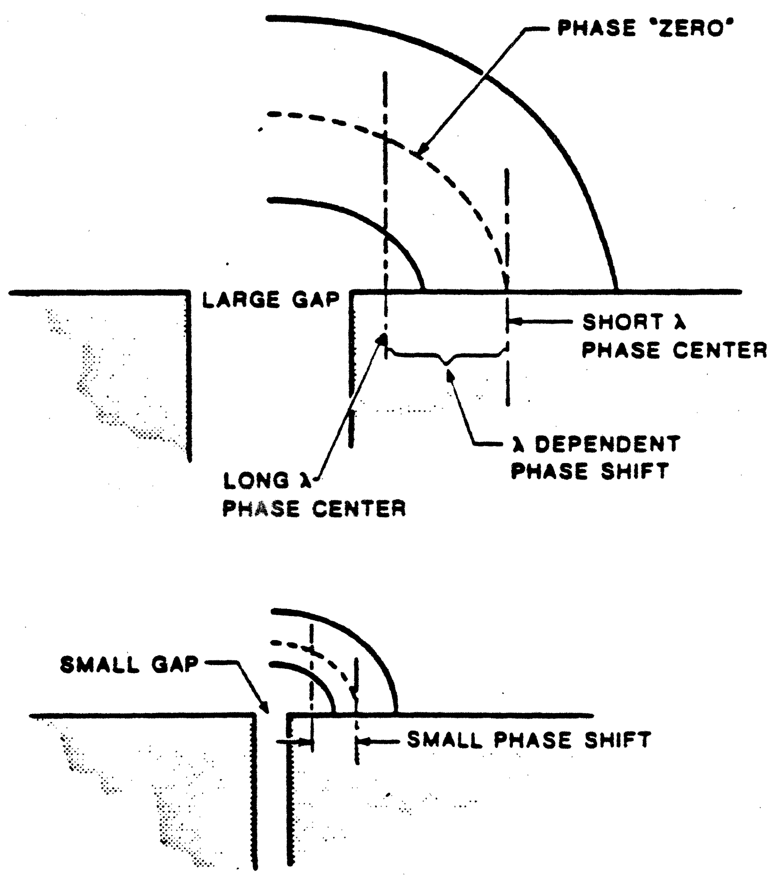


FIG. 5 SENDUST TIPPED BENCHMARK HEAD CROSS SECTION

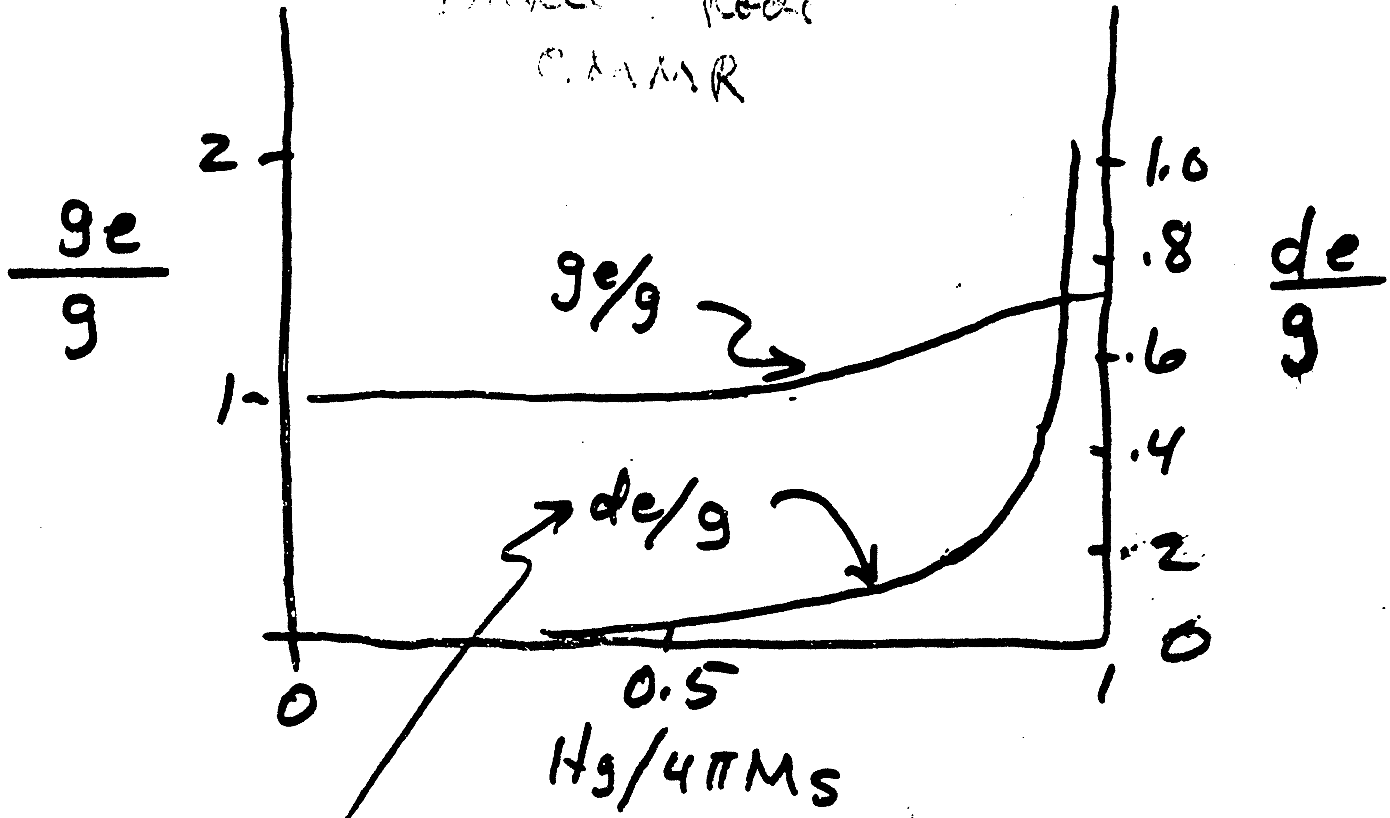
Smaller gap record heads also give less record phase shift, because the record zone has less curvature and what curvature there is has a smaller radius, i.e., the recording occurs closer to the gap, as shown in Fig. 6.

For applications such as disk storage devices, where no erasure takes place because old data is simply overwritten, Lemke[5] has shown that excellent overwrite of 30 dB can be obtained using 0.25µm record gaps at a density as high as 120 kFCI. Recent work has shown that optimum overwrite is obtained when $g = \lambda/4$, where λ is the wavelength of thesignal being overwritten.[6]

FIG. 6 WAVELENGTH DEPENDENT PHASE SHIFT FOR LARGE AND SMALL RECORD GAPS.



Dennis Rode'
CMMR



most important – data later

When $H_g \gtrsim \frac{4\pi M_s}{2}$, for ferrites, gap corners saturate, "gap" begins to open up => lower signal, and "separation" increases => lower signal.... all because L, record zone length, is increased.

In addition to the head fields acting on the medium, when the head and medium are not in "perfect" contact, there are also demagnetization fields arising from the media itself. In conventional media, these "demagnetization" fields tend to oppose the head record fields and, thus, smear out or increase the length of the record zone, reducing recording signal. They also lead to "nonlinear bit shift" where the location of a recorded transition is influenced by the demagnetization field of the preceding bit or string of bits. The demagnetization fields are limited to $4\pi Mrs$, while the record fields are proportional to Hc. Increasing Hc requires a proportional increase in the record field, and the demagnetization fields have less effect on the record zone, which allows more signal to be recorded and minimizes nonlinear bit shift. Increasing Hc also reduces the slope of the record separation loss for the same reason.

Gap Corner Saturation

Unfortunately, making record gaps smaller and coercivity higher in an effort to achieve more signal and less nonlinear bit shift at high density, requires higher gap fields to do the recording. In typical high permeability ferrites, like MnZn ferrite, when the gap field exceeds about half the saturation flux density $4\pi Ms$, the corners of the gap become saturated. This causes the record zone to become longer and loss of signal results. Hence, gap edge saturation sets a lower limit on the record gap length.

Equation (5) below relates the gap field Hg required to record maximum level signals of wavelength λ on a medium of coercivity Hc using a head of gap g where λ and g are in μm. Good head-to-media contact is assumed.

$$H_g \simeq \left(\frac{1.7}{g^{0.33}} + \frac{0.8\lambda}{g^{0.78}}\right) H_c \qquad (5)$$

This field is very nearly the same as the bias field in a bias recording so the conclusions apply there, as well as in unbiased recording. Equation (5) was obtained using record currents and other data obtained in generating the curves in Fig. 4 and similar curves using tapes of different Hc. It is an analytic fit to the data.

The apparent maximum in the g = 0.25μm curve at ~ 70 KHz or λ = 2.73μm in Fig. 4 is due to saturation in the Sendust pole tips of the record head. The saturation flux density of Sendust is ~ 9500 G and Eq. (5) gives Hg = 7800 Oe for λ = 2.73μm, g = 0.25μm, and Hc = 860 Oe. This gap field is 82% of saturation and causes gap edge saturation. Because the approach to saturation is abrupt in Sendust, gap fields significantly above 50% of saturation can be used.

Equation (5) can be used to determine whether a head design will suffer from saturation effects. For ferrites, if Hg is much larger than ~ 0.5 ($4\pi Ms$), saturation is occurring and a larger gap or a higher $4\pi Ms$ head material should be used.

Figure 7 shows the gap field above a ferrite audio head, measured with a scanning electron microscope, plotted versus record current.[7] Clearly, saturation is important at Hg = $4\pi Ms/2$ = 2000 Oe.

$4\pi M_s \simeq 4000G$ for $T_c \simeq 130C$ ferrite (MnZn)

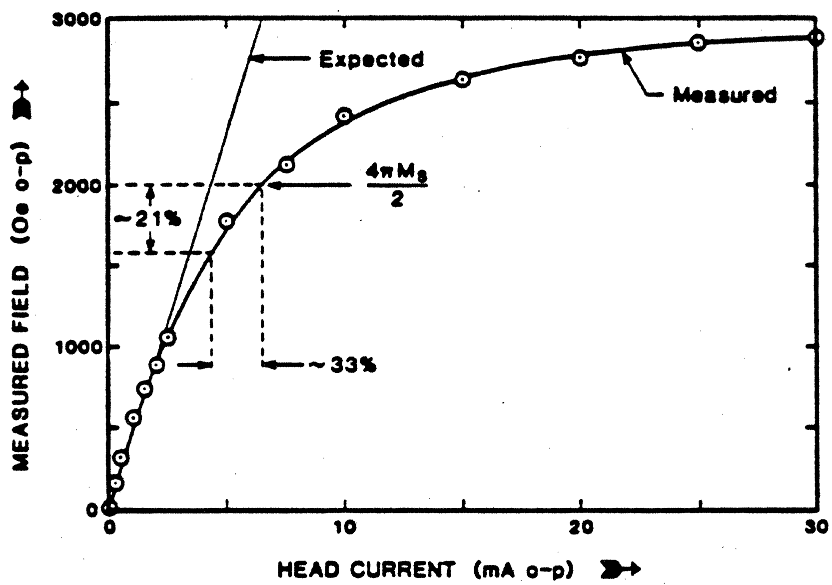
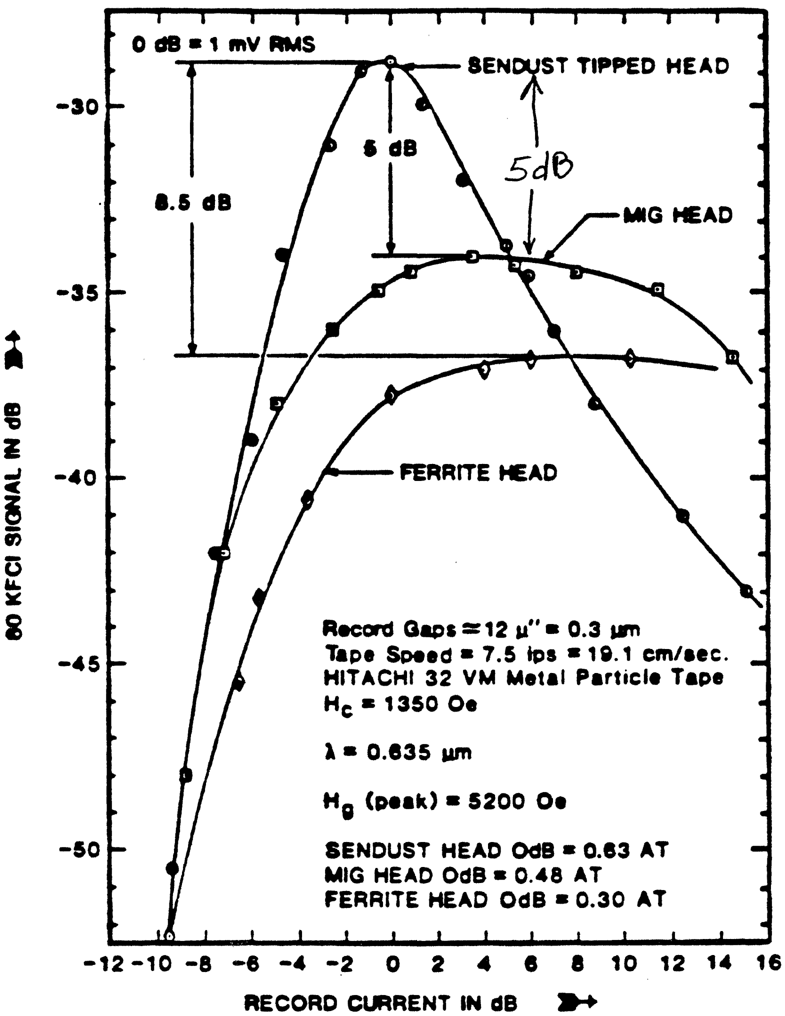


FIG. 7 FIELD VERSUS CURRENT FOR A 5 µm GAP FERRITE AUDIO CASSETTE HEAD.

NEWER ferrite with $T_c \simeq 190°$ have $4\pi Ms = 5000G$ and can achieve $Hg \simeq 2500$ before gap corner saturates

Figure 8 shows the comparative 80 kFCI signal recorded on a 1350 Oe coercivity metal particle tape by a Sendust tipped head, a MIG head (discussed below), and a ferrite head, plotted versus record current. The ferrite head signal is 8.5 dB below that recorded by the Sendust tipped head, even though both have the same 0.3µm gap.



$H_g \simeq 5200$ Oe

FIG. 8 80 KFCI SIGNAL RECORDED ON H_c=1350 O_e METAL PARTICLE TAPE BY SENDUST, MIG AND Mn Zn FERRITE HEADS VERSUS RECORD CURRENT.

bad for metal particle tape

Up to now, we have ignored the coercivity of the core, H_c (core), which can be as low as 0.05 Oe for well annealed MnZn. If the head is exposed to some sort of dc transient that saturates the core, the field in the gap which results can be large, if the gap length is as small as 0.25μm. Hg (core) is given roughly by

$$Hg\ (\text{Core}) \simeq Hc\ (\text{Core})\ \frac{c}{g} \qquad (6)$$

where C is the core circumference. Using H_c = 0.05 Oe and C = 1 cm with g = 0.25 x 10^{-4} cm, we have Hg (core) = 2000 Oe, which is more than half the 80 kFCI record field for an 800 Oe coercivity tape! This dc gap field will result in considerable second harmonic distortion and signal loss. A dc gap field of only 200 Oe will give enough second harmonic distortion to produce significant high-density peak shift and poor measured 1F/2F overwrite. Recording heads should always be "degaussed" prior to use. Commercial handheld units are available, or a "ring down/up" circuit can be built into the drive electronics.

For systems where the record head must also serve as the reproduce head, the maximum gap is limited to no more than ~ $\lambda/2.5$ because of the "gap loss term", approximated by the expression Sin (X)/X, X = $1.14\pi g/\lambda$.[8] Even for g = $\lambda/2.5$, the band edge signal loss is 3 dB.

Using g = $\lambda/2.5$ in Eq. (5) gives

$$H_g \simeq \left(\frac{2.3}{\lambda^{0.33}} + 1.63\ \lambda^{0.22}\right) H_c \qquad (7)$$

For densities of 50 to 100 kFCI, λ is 1 to 0.5µm and, over that range, the term in brackets above is nearly constant and equal to 4; hence,

$$H_g \simeq 4\ H_c \qquad (8)$$

If the record-reproduce head is ferrite, then Hg ≤ (4πMs)/2, and the result is that a coercivity of > Hc ≈ (4πMs)/8 should not be used. The saturation flux density for MnZn ferrite is generally ~ 5000 G, so that the maximum media coercivity one can safely use with a ferrite record-reproduce head is ~ 5000/8 ≈ 625 Oe.

NiZn ferrite should not be used because its 4πMs is only 4100 G which promotes saturation, and it tends to form a "dead layer" of several hundred angstroms which causes unacceptable separation loss.

If the head is Sendust tipped, a gap field up to ~ Hg ≈ 0.8 (4πMs) can be used because the metal has a more rapid approach to saturation than ferrite. Since 4πMs ≈ 9500 G, Eq. (8) gives Hc ≤ 1900 Oe, which is higher than that of any high-density medium yet reported.

Saturation and Eddy Currents in Metal Heads

Although small gap Sendust tipped heads can record on very high coercivity media at high frequencies, the flux is confined to the surface of the head by eddy currents in the conductive metal. This causes the gap field to be shifted in phase relative to the record current by various amounts, depending on frequency. In addition, because of saturation in the "skin" of the head, the efficiency E in Eq. (1), and hence Hg, can become much smaller for constant record current as the record frequency is increased. For example, experiments at various tape speeds indicate that the record efficiency of the 0.25μm gap length Sendust tipped heads used in generating Fig. 4 decreases from 52% at 10 KHz to only ~ 9% at 10 MHz. The reproduce efficiency was ~ 31% at 10 MHz.

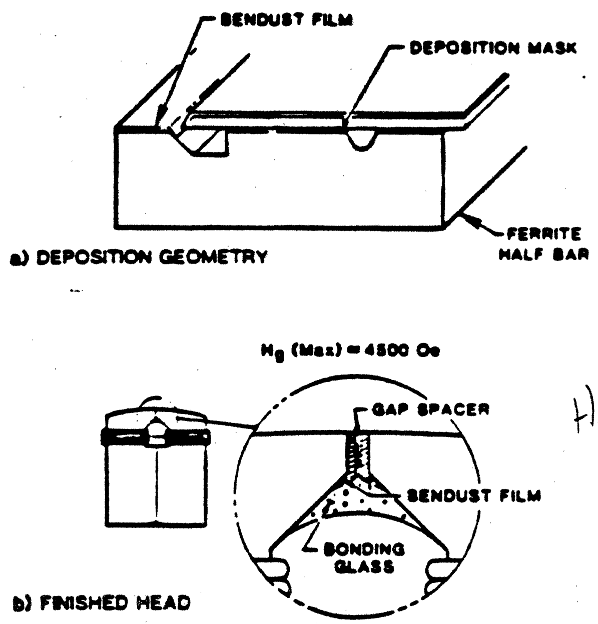
If a constant record current is used in these or other metal heads while recording high-frequency digital data, long strings of zeros (low frequencies) will be severely overrecorded, which causes peak shift and errors. Even if record current amplitude pre-emphasis is used to prevent this overrecording effect, there will still be a lot of hard-to-predict phase shift occurring in the record head itself, because of the eddy current-induced saturation. This phase shift and the required pre-emphasis will change as the head wears, and metals have a high wear rate. The frequency/saturation effect makes the Sendust tipped head, shown in Fig. 5, a poor choice for high-frequency recording use.

Heads have been made of crystalline Sendust and amorphous metallic quench-cooled ribbons.[9,10] These heads are easy to make in thin laminations, so they suffer less high-frequency degradation from eddy currents than unlaminated heads. The resistivity of the amorphous ribbons is higher than Sendust, so eddy currents are even less important, but the wear rate for several amorphous materials tested at our laboratories was ~ 5 times higher than Sendust. The high wear rates of amorphous metals has recently been confirmed.[11]

Metal-In-Gap Head

Figure 9 shows a new type of Sendust/ferrite composite head, where the Sendust is sputter deposited on the gap faces of an otherwise all ferrite head; thus, the name metal-in-gap, or MIG.[4]

FIG. 9 CONSTRUCTION OF MIG HEADS



$H_c \lesssim 10000$ Oe

Since the Sendust film and the ferrite core are magnetically in series, Hg is limited to the $4\pi Ms$ of the ferrite which is ~ 5000 G. Because the Sendust $4\pi Ms$ = 9500 G, the gap edges do not saturate at this gap field, and the maximum gap field for the MIG is Hg = 5000 Oe. Using Eq. (3), we see that an Hc = 1250 Oe can be used with an MIG record/reproduce head without pole-tip saturation being a problem. The efficiency of this head is much less frequency-dependent than that of the metal-tipped head; it is fine for recording digital data at high frequencies on high coercivity media.

The reason that the MIG curve in Fig. 8 is not as high as that of the Sendust tipped head is probably because of a small amount of "pole-tip erosion" induced record separation loss, as shown in Fig. 14. This effect is much less important at high media speed. It is also likely that the metal particle tape in Fig. 8 is rougher than the tapes used in generating Eq. (5). This requires a somewhat higher gap field to saturate the medium to the required depth and causes the apparent coercivity to be larger than the measured value of 1350 Oe.

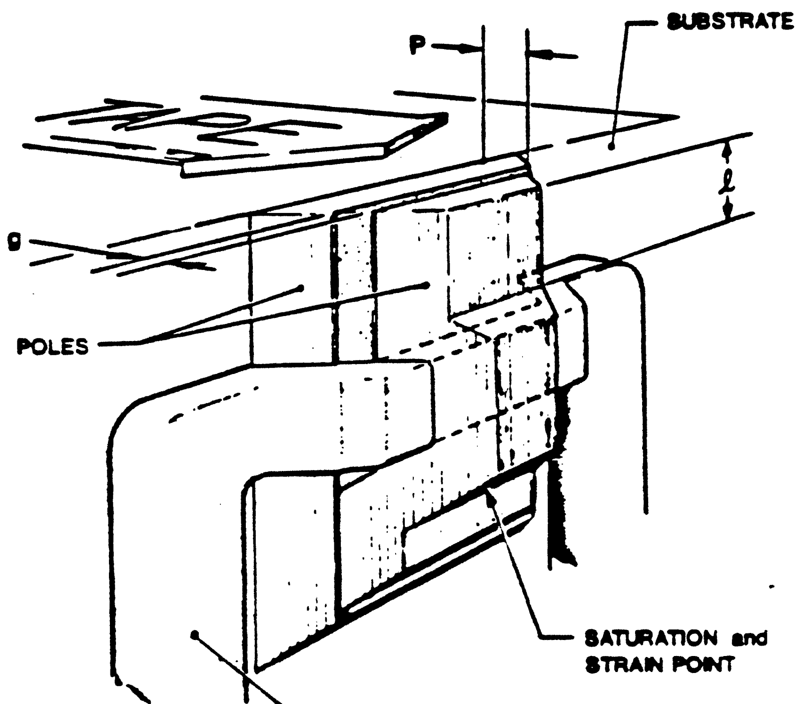
The MIG heads also work well in reproduce. However, care must be taken to prevent any nonmagnetic material from being deposited between the Sendust and the ferrite. This eliminates bumps in the frequency spectra from the resultant extra gaps.

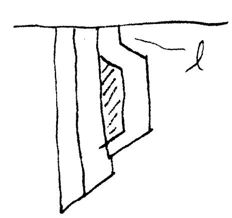
Thin-Film Record Heads

A simple one-turn thin-film head is shown in Fig. 10. Multiple-turn heads have also been made.[12] The poles are typically sputter deposited or electroplated 81% nickel and 19% iron, having a permeability of ~ 2500 and a $4\pi M_s$ of 10^4 G. The structure is fabricated photolithographically. Integrated circuits are made in a similar way.

FIG.10 SINGLE TURN THIN FILM HEAD

$H_g \overset{NA}{\approx} 4\pi M_s \frac{P}{\ell}$

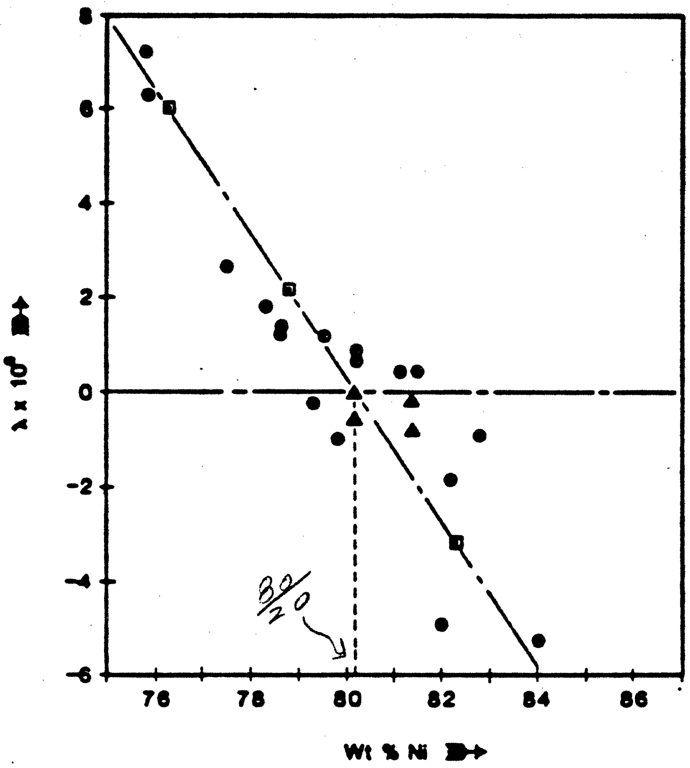




Cover plate not shown for clarity.

The composition of 81/19 NiFe is important, because its magnetostriction constant is zero. Figure 11 shows the magnetostriction constant plotted versus composition. When films are deposited at an oblique angle, as occurs at the "shoulders" in Fig. 10, the films are invariably strained to some degree. If λ is not very small, this strain can reduce the effective permeability of the shoulders by a factor of 5 or 10; hence, drastically reducing head efficiency.

FIG. 11 MAGNETOSTRICTION VERSUS COMPOSITION FOR Ni/Fe



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The pole thickness p, for high-density recording, is typically ~ 4μm. This thickness is about the maximum that can be processed conveniently by photoresist and ion mill etching at the ≈ 3μm line width resolution required for high track density multitrack heads. Track densities of up to ~ 500 TPI on two interleaved stacks can be made this way. The gap depth ℓ is determined by the wear rate of the substrate and the expected life of the head. The gap depth needs to be as small as possible because the ratio p/ℓ determines the maximum Hg that can be generated.

At low gap fields (and in reproduce), the efficiency of this sort of head is generally high when p ≈ ℓ.[13,14] However, when the gap flux (per track width) Hg·ℓ approaches the pole layer saturation flux 4πMs·p, the core saturates in the region noted in Fig. 10, and no further gap field increase occurs. The saturation gap field is given by Eq. (9).

$$H_g^{max} \propto 4\pi M_S \frac{p}{l} \qquad (9)$$

must increase? & reduce l. Both awkward to do.

Figure 12 shows a sketch of the gap field versus record current i_r for $g = 0.25\mu m$ and various p/l values.

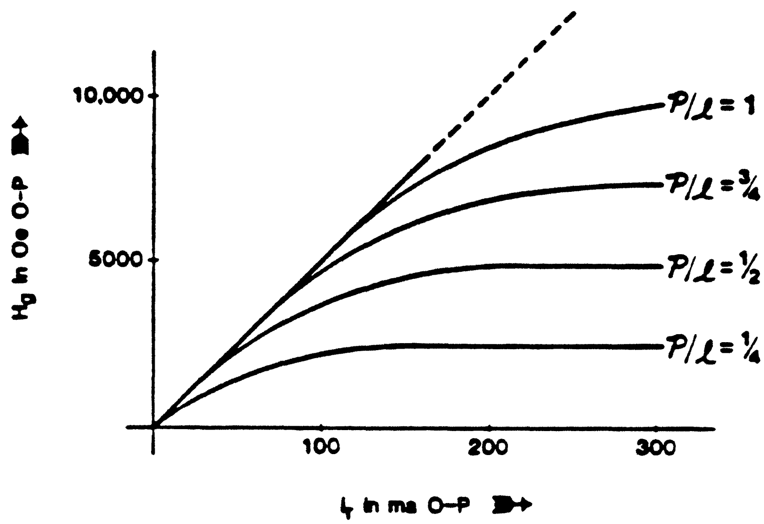


FIG.12 H_g versus i_r for single turn record head with g = 0.25 µm and various P/l values.

In thin-film heads for hard disks, the poles are made thinner in the gap region in an effort to reduce pulse crowding and improve "resolution" or ratio of 2F to 1F signal. 2F denotes the band edge or highest signal frequency. Because of this pole thinning, saturation typically occurs in the gap region, but the effect is still as shown in Fig. 12. This pole thinning technique is not practical in high-density recording because of the very small dimensions that would be required.

Figure 13 shows a sketch of the 80 kFCI signal recorded by a 0.25µm gap single-turn record head with two gap depths, plotted versus record current in dB. Also plotted is the corresponding curve for a Sendust tipped head, which does not saturate in this current range. The curves in Fig. 8 have been shifted horizontally to compensate for differences in low field efficiency.

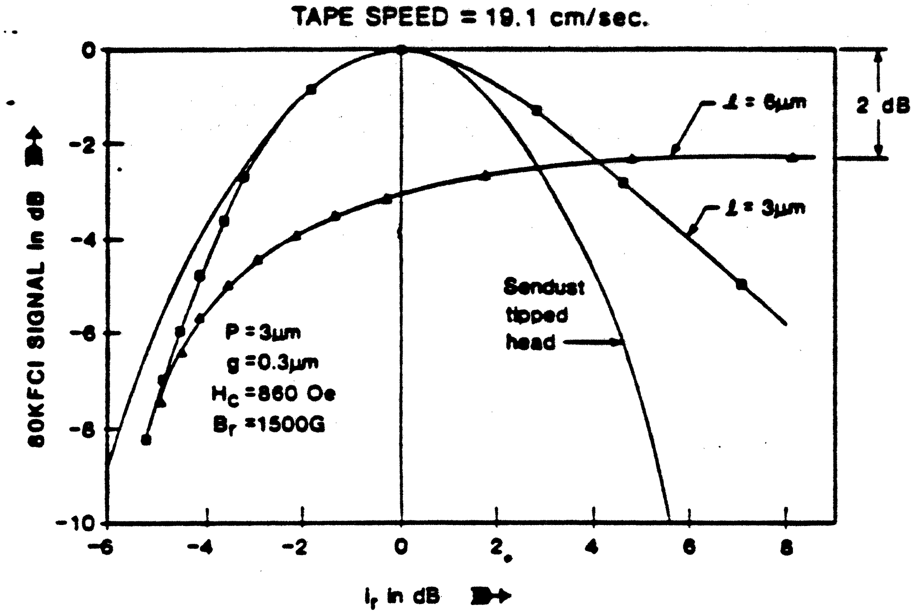


FIG. 13 80 KFCI or λ = 0.635µm signal level versus record current for a single turn head.

As may be seen, the p = 3µm, ℓ = 3µm head does succeed in saturating the tape, while the ℓ = 6µm head does not. Zero dB is 180 ma (pp) for the ℓ = 3µm curve.

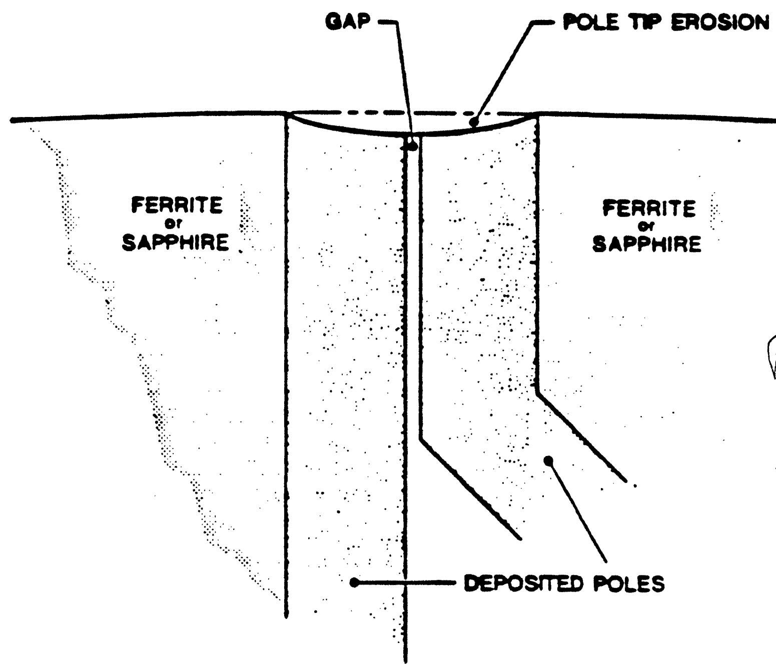
If a MnZn ferrite substrate is used, the bottom pole can be eliminated. If the top deposited pole is downstream of the gap, the partial saturation of the ferrite gap corner is of little concern, because it is so far from the record zone. This head would look similar to the single-sided pole vertical recording shown in Fig. 18b, but the pole would be much thicker and the gap would be much smaller than that shown.

Head Wear

Because of the stringent requirement for minimum head-to-medium spacing, the head-to-medium pressures may need to be high, which increases the wear rate. As the gap is reduced, so is gap depth in order to maintain head efficiency; hence, head life is reduced.

Fortunately, thin-film and MIG head materials, such as sapphire and ferrite, are much more resistant to wear than Sendust and Permalloy used in conventional heads. The wear rate of ferrite is ~ 10 times less than that of Sendust, and the wear rate of sapphire is so small that it is difficult to measure at nominal head-to-medium pressures.

An important problem with MIG and thin-film heads running in contact is that the softer metal layers tend to erode due to differential wear, as shown in Fig. 14. Since so little metal is exposed, the undercut is only ~ 0.05μ, but at a recording density of 100 kFCI, even this tiny amount gives about 4.5 dB record and 5.5 dB of reproduce separation loss for a total of 10 dB. This effect is much less important at high medium speed. Apparently the "gouging" particles need time to protrude from the medium surface after being pushed in by the hard substrate.



Better tape → less wash out

Tradeoff between media wear and pole tip erosion

FIG. 14 MIG and thin film head showing pole tip erosion.

Record Heads for Thin-Film Media

Equation (5) relating Hg, λ, g, and Hc was obtained from data generated using thick particulate-coated media. If deposited thin-film media are being recorded, where the media thickness is comparable to the record gap, Eq. (5) does not hold and ferrite heads can be used with Hc values much higher than 625 Oe. Here, one assumes that H = Hc at the back of the medium, as sketched in Fig. 15.

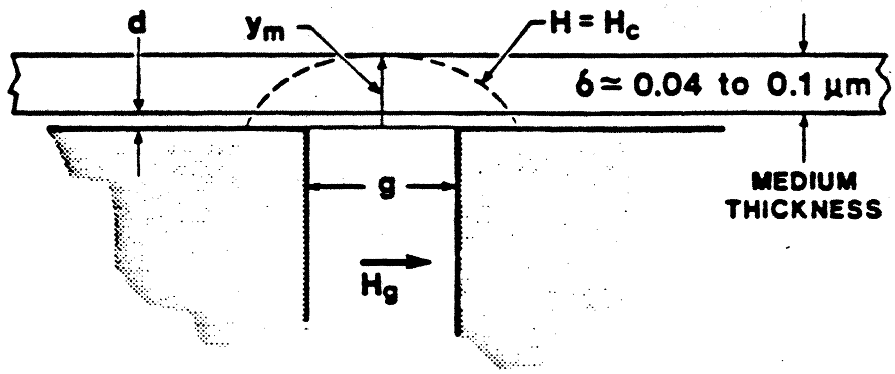


FIG. 15 RECORD CONTOUR FOR THIN FILM MEDIA.

The field is written in terms of the Karlqvist approximation.[15]

$$H_x = \frac{H_g}{\pi}\,(A1 - A2) \tag{10}$$

and

$$H_y = \frac{H_g}{\pi}\,\ln\,(R1/R2) \tag{11}$$

where the angles and distances are defined in Fig. 16.

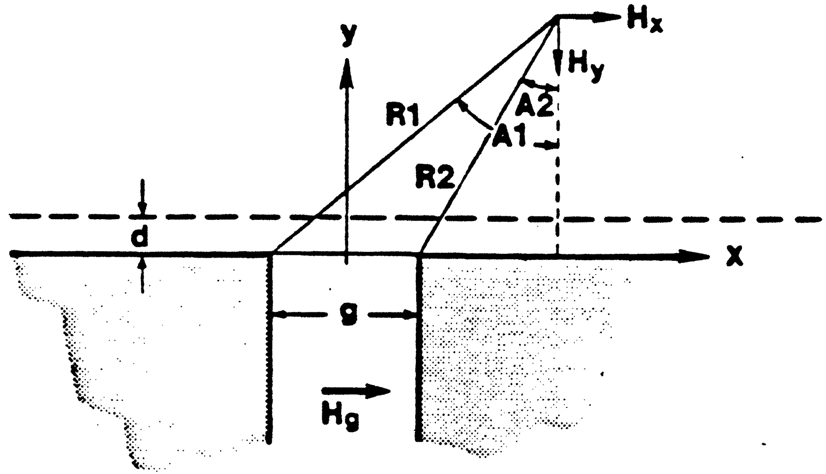


FIG. 16 ANGLE & DISTANCE FOR EQUATIONS 10 &11.

These expressions were used to sketch the field contours in Fig. 2 where $H = |\overline{H}| = \sqrt{(Hx)^2 + (Hy)^2}$. Defining Y_m to be the height of the $H = Hc$ contour at the back of the medium, at $x = 0$, we have

$$\frac{Y_m}{g} = \left[2\tan\left(\frac{\pi\, H_c}{2\, H_g} \right) \right]^{-1} \simeq \frac{1}{2.95}\left(\frac{H_g}{H_c} \right) - 0.15 \qquad (12)$$

The exact expression and approximation are plotted in Fig. 17. The approximation is good for $y/g \geq 0.4$ and is easier to remember and calculate. The Karlqvist expression, Eq. (12), becomes invalid for y/g much less than 0.4 because the point of maximum penetration moves away from the gap center.

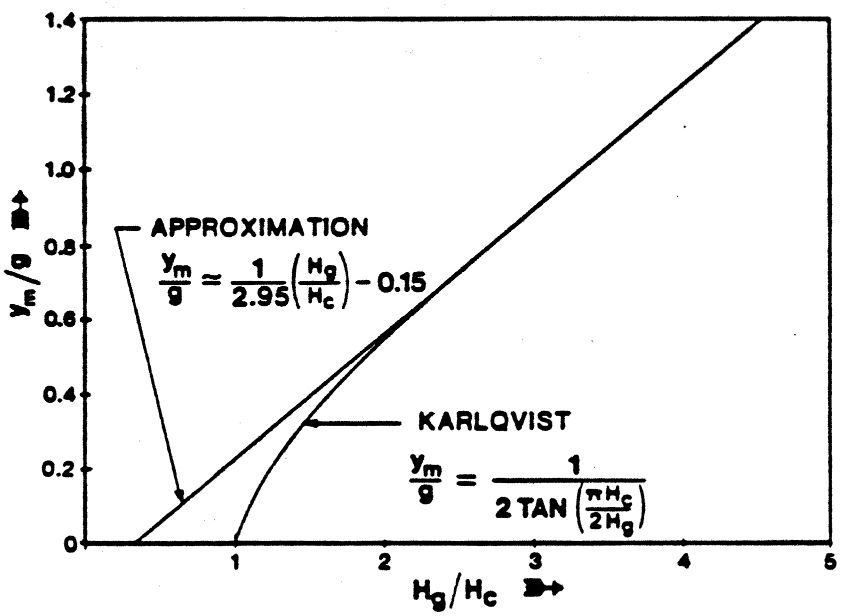


FIG. 17 PLOT OF $\frac{y_m}{g}$ VERSUS $\frac{H_c}{H_g}$

Solving Eq. (12) for Hc, and saying Hg $\leq$ (4πMs)/2 = 2500 Oe for the ferrite head material, gives

$$H_c \lesssim 847/\left(\frac{Y_m}{g} + 0.15\right) \qquad (13)$$

If Ym/g = 0.5, Eq. (13) gives Hc $\leq$ 1300 Oe for the maximum Hc that can be used with a ferrite head when the medium is very thin. This is a factor of two higher than the 625 Oe upper bound determined previously for thick media.

Highest density recorded on CoCr with keeper layer, D(50) = 630 k FCI. But must be in contact --- metal to metal --- wear is bad! NiFe keeper layer is part of the head, it produces a lot of noise. CoCr is subject to corrosion. Two ⊥ rec. Co. now out of business, Lanx and Vertimag. Japanese still interested, no products.

RULE OF THUMB

when $g = \frac{\lambda}{2}$

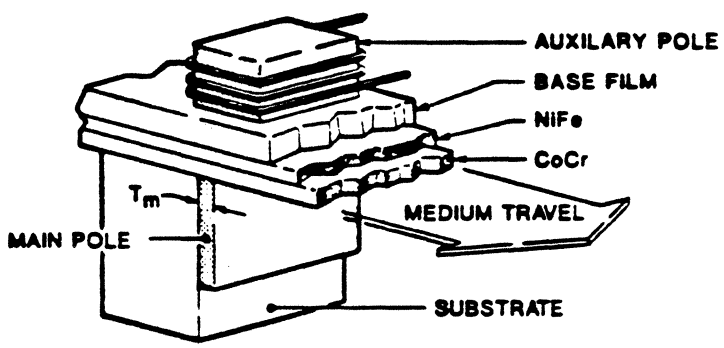
$y \simeq g$

$H_g \simeq 3.4\ H_c$

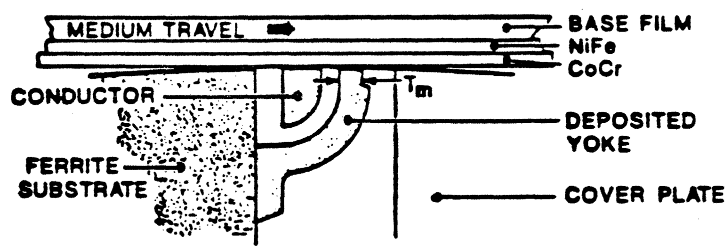
Vertical Recording Heads

In vertically oriented media such as sputter-deposited CoCr,[16] the demagnetization fields coming from the previously recorded bit aid the record field in recording the next bit, rather than opposing it as in conventional media. This results in a narrower record zone; hence, a larger high-density signal and less nonlinear bit shift. Conventional ring record heads work well with vertical media, because at the surface of the media where most of the high density signal resides, the record field is vertical. However, a narrower record zone and improved record performance is obtained with vertical pole heads, as shown in Fig. 18, when recording on two-layer vertical media.[16]

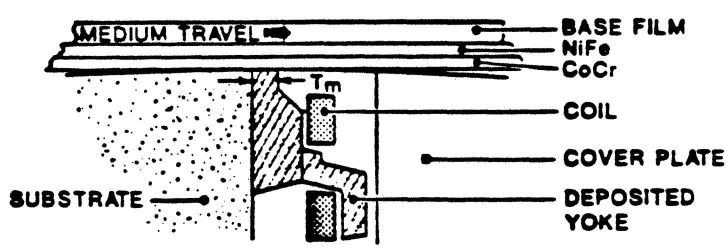
FIG. 18 VERTICAL HEADS



a) VERTICAL RECORDING AUXILARY POLE HEAD.



b) CROSSECTION OF SINGLE TURN ONE SIDED VERTICAL HEAD.



c) CROSSECTION OF ONE SIDED SINGLE POLE HEAD.

Toda[17] has compared the record capability of the head shown in Fig. 18c, having a pole thickness Tm of 1.2μm, to a ferrite ring head having a very small gap of 0.16μm. Both were tested on a two-layer CoCr medium. The pole head recorded up to 7.6 dB more signal than the ring head and the ring head pulses were very asymmetric. This indicates that significant horizontal moment, as well as vertical, was recorded by the ring head, which complicates reproduction. Pole heads seem better than ring heads for recording on two layer-vertical media.

However, when recording on single-layer vertical media, very high current levels are required with pole heads, because demagnetization fields in the pole tip are very high. Magnetomotive forces, Ni_r, of 30 amp turns are common for the single layer, while only 2 amp turns are needed for the two-layer medium, because of the "magnetic image" of the record head provided by the NiFe layer.

Futamoto[18] has recently shown that D50 densities (where the signal is down 50% from the peak value) of 230 kFCI can be recorded successfully on single-layer CoCr media, with little pulse asymmetry using ring heads, if the CoCr anisotropy field is large and the layer is very well oriented by depositing it on a "seed" layer of Ge or Ti.

Reproduce

The output voltage of an inductive reproduce head is given by

$$S = -10^{-8} N \frac{d\phi}{dt} \tag{14}$$

where S is in volts, N is the number of turns, and ϕ is the flux in the head in Maxwells (cgs emu or Gauss cm^2). The head flux ϕ is determined by the reciprocity principle[8]

$$\phi = \int \bar{M}_r \cdot \bar{H}\, dv \tag{15}$$

where Mr is the recorded remanence in the medium and H is the field above the read head generated by a unit "test current" in the reproduce windings. The integral is over the volume of the tape. For a ring head, H is given by Eqs. (10) and (11) and, in this context, is called the "read head sensitivity function."

H is connected to the head efficiency by Eqs.(1)-(4) which can be used to highlight a trade off in head life and linear density. If one assumes a maximum gap loss of 3 dB, then $g \leq \lambda_b/2.5$, where λ_b is the shortest wavelength. Assuming a constant efficiency to maintain signal-to-noise ratio, if the core cross section, circumference, and permeability A, C, and μ are held constant, it is easy to use Eqs. (2)-(4) to show that the gap depth ℓ and, hence, head life is inversely proportional to linear density.

Equation (15) can be broken down into horizontal and vertical components as:

$$\Phi = \int M_{rx} H_x \, dv + \int M_{ry} H_y \, dv \qquad (15a)$$

If Mrx = Mry are the amplitudes of respective sine waves, the two terms above are equal, except for a 90° phase shift; hence, equal horizontal and vertical sine wave magnetizations produce the same read signal amplitude.

We can get a rough idea of the expected signal amplitude S if we make the crude approximation that the medium is sinusoidally magnetized in the x direction at the saturation level, i.e.,

$$M_{rx} = M_{rs} \sin\left(\frac{2\pi}{\lambda} x\right), \qquad (16)$$

$M_{ry} = 0$

to a depth δ and is unmagnetized beyond that. The geometry is shown in Fig. 2b. Combining Hx from Eq. (10) and Mrx from Eq.(16) in Eq. (15a), putting ϕ into Eq. (14), and doing a Fourier transform, gives the simple expression

$$S = Ae^{-(2\pi+5)d/\lambda}\left[1-e^{-2\pi\,\delta/\lambda}\right]. \qquad (17)$$

$-55\,d/\lambda$

$-44\,d/\lambda$

gap null

$$\cdot \frac{\sin(1.14\pi\, g/\lambda)}{(1.14\pi\, g/\lambda)} \text{ p-p in Volts}$$

where

$$A = 2 \times 10^{-8}\, ENTv\, 4\pi\, M_{rs}. \qquad (18)$$

The first term in the exponent in Eq. (17), $-2\pi d/\lambda$, gives the $-55d/\lambda$ db reproduce separation loss, and the second, $-5d/\lambda$, gives the $-44d/\lambda$ dB record separation loss, both discussed earlier. The record separation term did not come from Eq. (15a), but was added. The term in brackets is the "thickness loss term" and gives "6 dB/octave" increase at long wavelength and shows that 90% of the signal comes from the top λ/e of the layer. Hence, little is gained by making $\delta > \lambda/e$. The third term is the "gap loss term." It is unity at long wavelength and zero when $\lambda = 1.14g$,* having subsequent "bumps" as the wavelength is further reduced.

E in Eq. (18) is the reproduce head efficiency given by Eq. (2), or more accurately, by Eqs. in Ref. 1. N is the number of turns on the reproduce head, T is the track width in cm, and v is the media velocity in cm/sec. $4\pi M_{rs}$ is the saturation remanence flux density in Gauss, i.e., 100% in Fig. 1 or ~ 1200 G for most tapes.

Figure 19 shows a response curve obtained using the 0.25μ gap record head, a 0.25μm gap reproduce and tape used to obtain the data shown in Fig. 4.

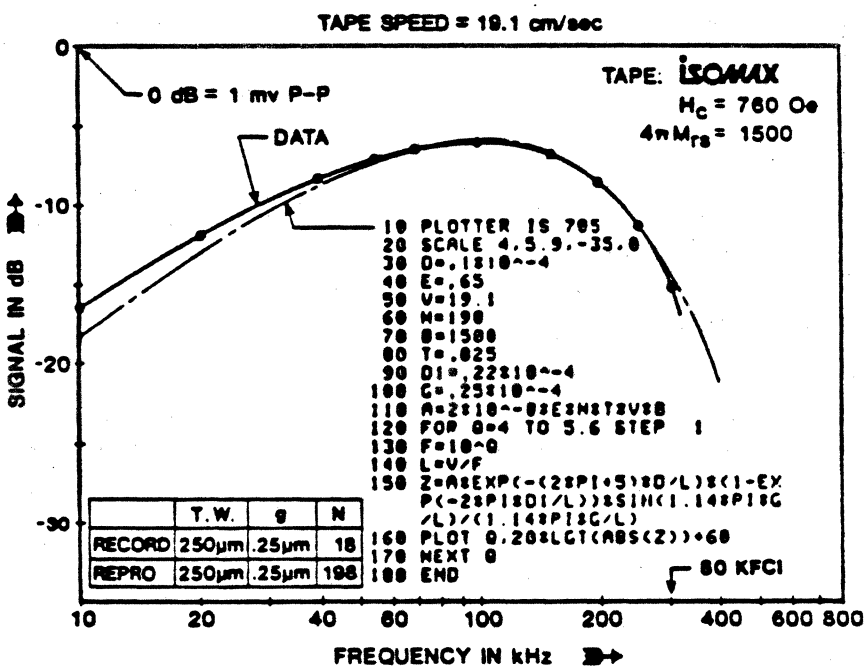


FIG. 19 SINEWAVE RESPONSE CURVE
AND COMPUTER FIT.

The recording was unbiased sine wave with the record current held constant and set to maximize the 300 KHz or $\lambda = 0.635 \mu m$ signal. Using a record gap $g = 0.25 \mu m$ and $\lambda = 0.635 \mu m$ in Eq. (5) gives $Hg/Hc \cong 4.2$. Using this in Eq. (12) gives $Ym/g = 1.27$ or $Ym \cong 0.32 \mu m$. $4\pi Mrs$ for the tape used was 1500 G, the reproduce turns were $N = 198$, the track width was $T = 0.025$ cm, and the tape speed was $v = 19.1$ cm/sec. The reproduce gap was also $0.25 \mu m$. A reasonable upper bound on the reproduce head efficiency was $E \cong 0.65$, and a head tape separation of $d = 0.1 \mu m$ was picked to give a good fit. The thickness of the recorded layer $\delta = Ym - d$ or $0.22 \mu m$. Using these values in Eqs. (17) and (18) gives the Hewlett Packard HP-85 computer-drawn curve in Fig. 19. The program is also shown. The fit is within ~ 2 dB, which is surprising considering the gross approximations made and the fact that only two variable parameters were used; head-to-tape separation δ and head efficiency E. The curve shape is determined solely by δ. E simply moves the curve up and down on the vertical axis.

In digital recording, one records "square waves." Figure. 20 shows the data in Fig. 19 and a square wave response curve done at the same time. At short wavelengths, the higher odd harmonics which make up the square wave do not come through the record/reproduce process so the sine and square wave signals are the same.

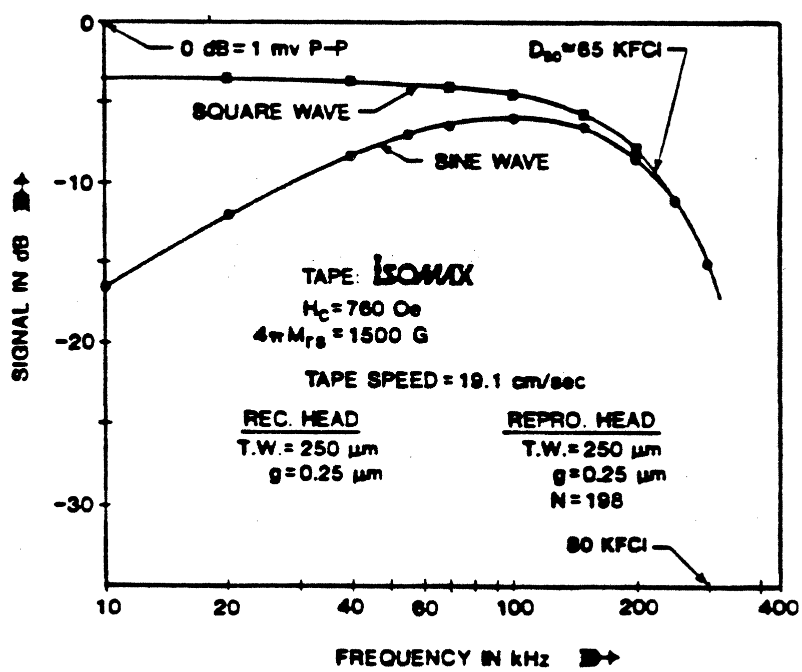
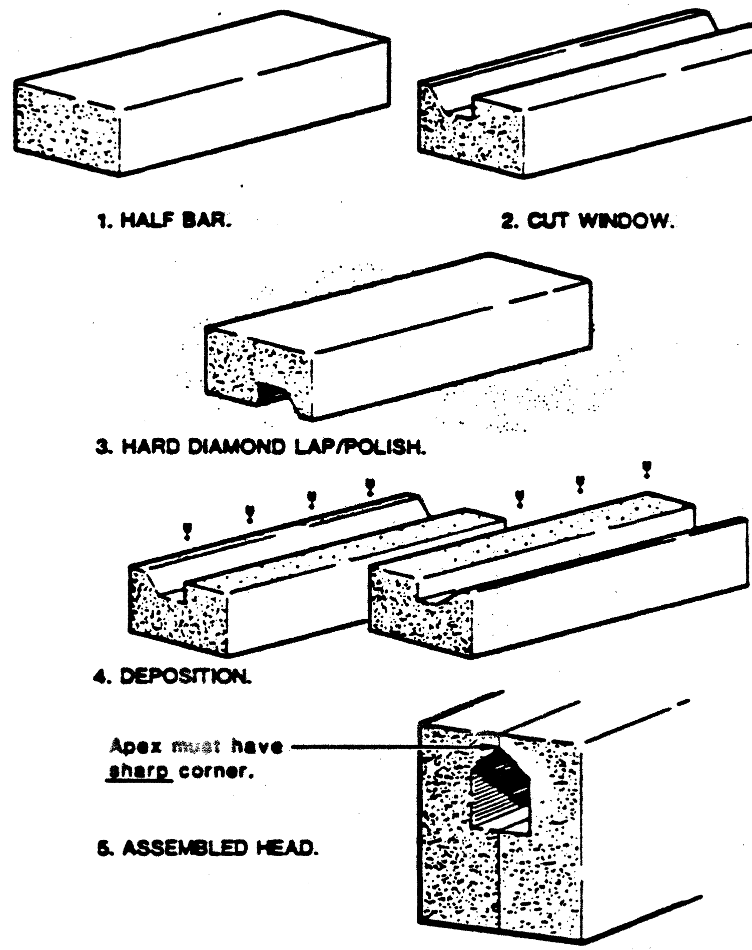


FIG. 20 COMPARISON OF SINEWAVE AND SQUAREWAVE RECORDING. RECORD AND REPRODUCE HEADS ARE SENDUST TIPPED.

Gap Edge Straightness

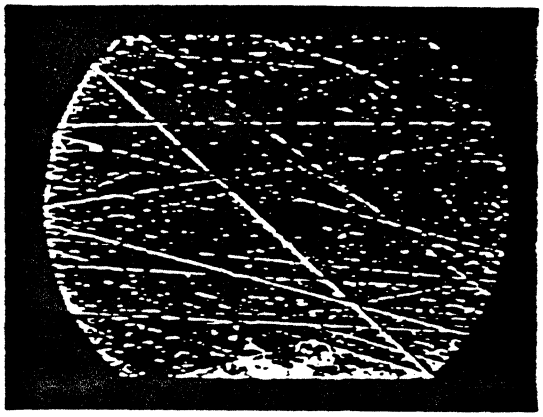
In the past, the standard procedure for making heads has been to cut a region for the turns (the "current window") and then polish the gap surfaces. Because of this sequence, the final polish must be a hard diamond lap in order to preserve a sharp corner at the gap apex, as shown in Fig. 21.

FIG. 21 TRADITIONAL HEAD CONSTRUCTION.

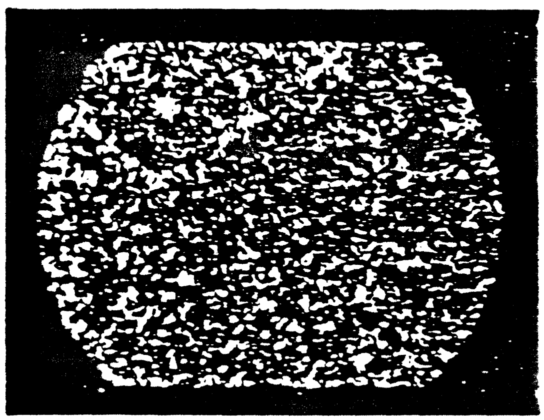


This procedure results in a gap surface covered with tiny scratches. Figure 22 shows typical gap surfaces of ferrite and Sendust tipped heads.

FIG. 22 DIAMOND LAPPED GAP SURFACES AT 950X



FERRITE HEAD GAP SURFACE.

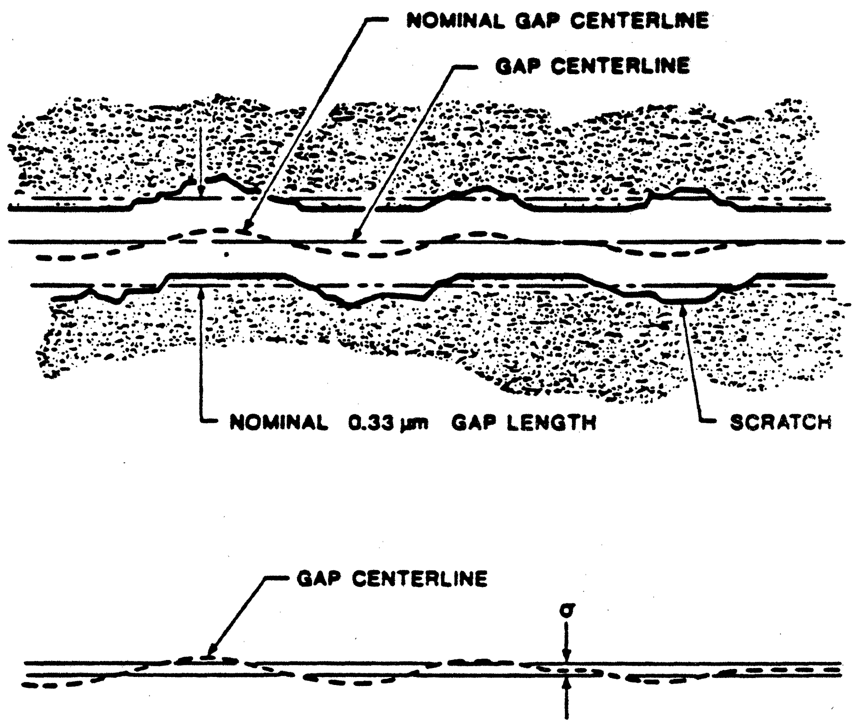


SENDUST TIP GAP SURFACE.

The contrast of these photographs has been greatly increased with Nomarski differential interference enhancement.

The smallest scratches are too small to measure, but many are as large as 1 μm across, and probably up to 0.5μm deep. When the head is assembled the gap looks, in a somewhat exaggerated way, as shown in Fig. 23.

FIG. 23 Top view of a head with scratched gap faces at about 50,000X (!).



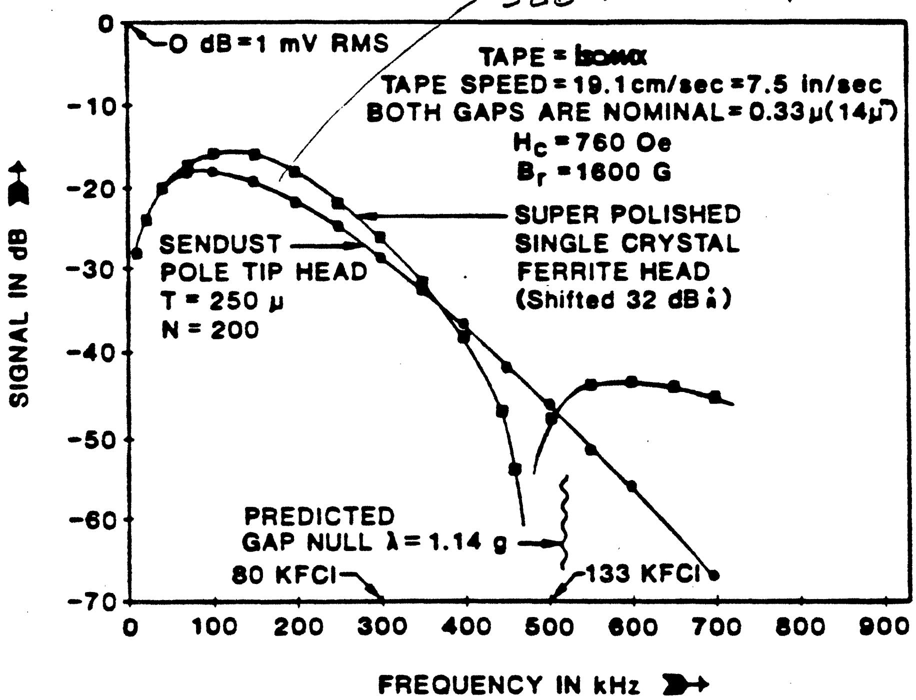
σ = RMS GAP CENTERLINE STRAIGHTNESS DEVIATION

The gap length variation shown in Fig. 23 washes out the gap null. Figure 24 shows a 250μm track width Sendust pole tip reproduce head spectrum, which is linear where the gap null should be. Also shown in Fig. 24 is the reproduce spectrum of a 36μm track width single-crystal MnZn video head with the same gap.

GAP IRREGULARITY LOSS $\simeq 169\left(\frac{\sigma}{\lambda}\right)^2$ db

FIG. 24 RESPONSE CURVE SHOWING REPRODUCE GAP NULL BEHAVIOR.

3db $\Rightarrow \sigma = 0.18\,\mu m$



The ferrite head curve was shifted up to compensate for differences in track width, turns, and core efficiency. The ferrite head shows the expected gap null because its gap surface was "superpolished" using a colloidal SiO_2 lap,[19] which results in a surface finish as shown in Fig. 25. Nearly all of the artifacts visible are dust in the micro-scope optical path.

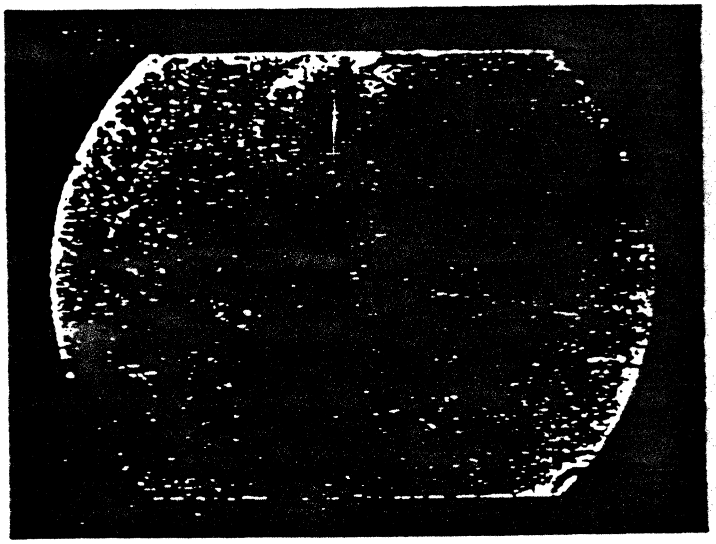


FIG. 25 FUJI Mn Zn SINGLE CRYSTAL SUPER POLISHED WITH COLLOIDAL SiO_2 AT 950X.

This lapping technique results in a close to perfect surface finish, but it tends to round off corners, so it is necessary to lap the gap surface and then cut the current window to preserve the sharp corner at the gap apex. This requires care to avoid chipping.

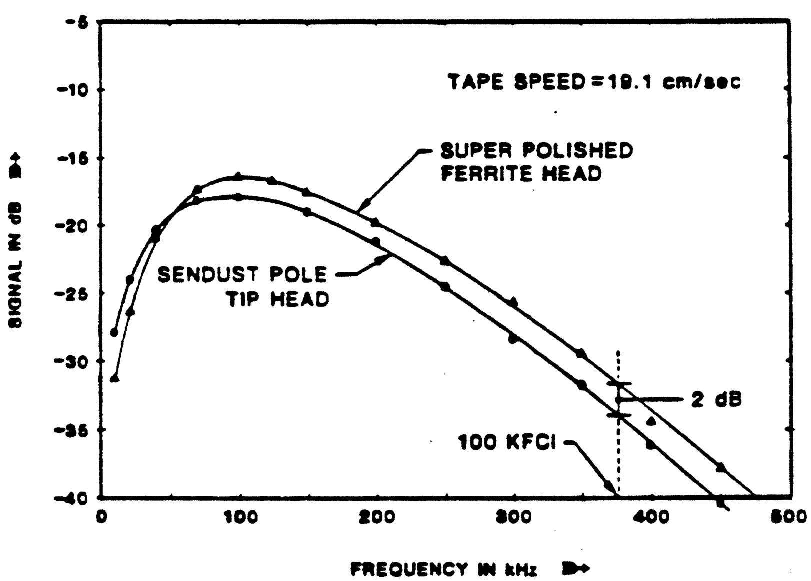
The important thing to note in Fig. 24 is that the reproduced signal at intermediate and band-edge densities is up to 3 dB higher for the ferrite head. The reason for this is that the gap center line for the Sendust tipped head is not straight, as shown in Fig. 23. When this occurs, various parts of the recorded track produce signals that are out of phase and tend to cancel, resulting in less signal. Mallinson[20] has shown that if σ represents the average gap center line deviation, then the "gap irregularity loss" on reproduce is given by

$$\text{Gap Irreg. Loss} \simeq 169 \left(\frac{\sigma}{\lambda}\right)^2 \text{dB} \qquad (19)$$

Noting that the difference between the ferrite and Sendust tipped heads is 3 dB at 200 KHz or $\lambda = 0.95\mu m$, solving Eq. (19) for σ gives $\sigma = 0.18\mu m$ which is reasonable in view of the multitude of scratches shown in Fig. 22.

Figure 26 shows the comparative record spectra of the two heads. The "superpolished" ferrite head curve was adjusted upward to compensate for track width differences. Both curves were reproduced with the same Sendust pole tip read head; hence, no gap null is evident.

FIG. 26 RECORD PERFORMANCE OF SENDUST TIPPED AND SUPER POLISHED FERRITE HEADS.



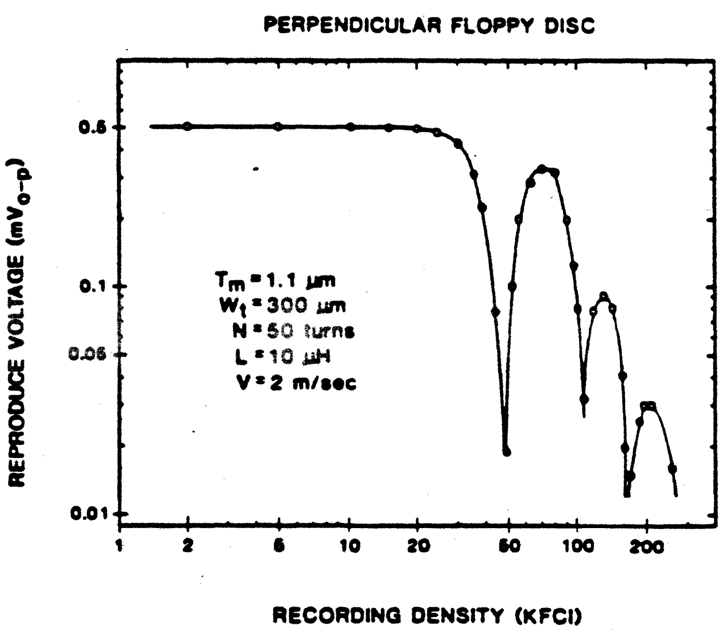
The "superpolished" ferrite head records ~ 2 dB more midrange and high-density signals and the advantage is independent of wavelength for $\lambda \leq 1.75\mu m$. The source of this advantage is not obvious. The local "record phase cancellation" one might expect from the gap center line deviation of the Sendust tipped head is apparently compensated for by gap length variations. Where the gap is small, the record fields are large, and vice versa. This might tend to straighten out the recorded transitions.

One possible explanation for the more or less wavelength-independent advantage of the "superpolished" head is that there is significant record field direction variation along the Sendust tipped head gap. Since ISOMAX medium accepts magnetization in any direction, the net result could be a reduced component in the tape travel direction at the surface of the tape; hence, a reduced signal at medium to short wavelengths. The straight gap edges of the ferrite head record full magnetization in the tape travel direction, which gives maximum detected signal. Note that this ferrite head records very well on this Hc = 800 Oe tape, in spite of a small amount of gap edge saturation, because $\lambda/g \approx 1.9$ rather than $\lambda/g = 2.5$ as specified in deriving Eq. (8).

Vertical Pole Heads in Reproduce

The vertical heads shown in Fig. 18 work well in recording on keepered vertical media, but in reproduce they suffer from gap nulls caused by the thickness of the main pole T_m. Figure 27 shows a typical example where $T_m = 1.1\,\mu m$.

FIG. 27 VERTICAL POLE HEAD RECORD/REPRODUCE



From a lecture by Prof. Jack Judy
Univ. of Minn., Elect. Engr. Dept.

This head is not usable beyond ~ 40 kFCI. If T_m is reduced, to move the gap nulls out to higher density the record function suffers, apparently because of pole tip saturation, and the medium thickness must be reduced, which lowers midband and low-density signal.[17] The reproduce efficiency is also lowered if T_m is reduced. Higher $4\pi Ms$ materials, such as amorphous CoZrNb, which has $4\pi Ms = 13{,}000$, are now being developed for pole heads to avoid the saturation problem. Care must be taken in processing CoZrNb, because its anneal temperature is rather low.

MR Read Heads

MR heads generally use a 200-500 Å thick single domain layer of 81/19 NiFe Permalloy, whose resistivity changes in response to rotation of the film magnetization vector according to the expression[21]

$$\rho = \rho_0 + \Delta\rho \cos^2\theta \qquad (20)$$

where θ is the angle between the current and the magnetization of the film, ρ_0 is the isotropic resistivity, and $\Delta\rho$ is the magnetoresistivity. The deposition takes place in a magnetic field which gives rise to an internal anisotropy field Hk. This field exerts a torque on the magnetization which acts to keep $\theta = 0°$, the so-called "easy axis". Hk is ~ 3 to 10 Oe. The sensor carries a constant sense current i_s and the field from the recorded medium rotates the moment, changing the resistance, which varies the voltage across the MR element producing a signal. Figure 28 shows a sketch of an MR element.

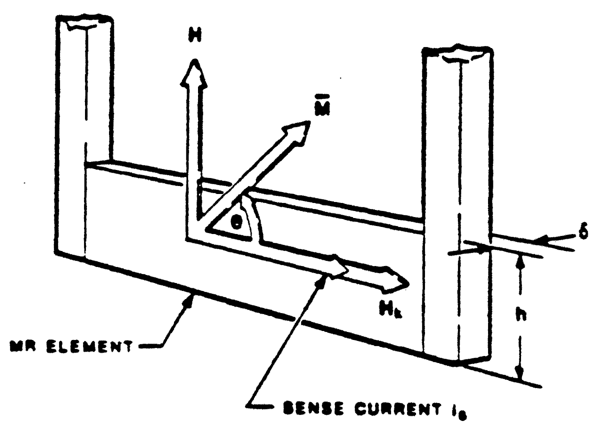


FIG. 28 MR ELEMENT

Figure 29 is a sketch of $(\rho-\rho_0)/\rho_0$ versus applied field H. The "skirts" of the curve are due to minor local deviations in the direction and magnitude of the anisotropy field Hk, called dispersion, and also due to any (nonuniform) demagnetizing fields Hd that may exist. The dotted curve in Fig. 29 shows how a perfect film would behave.

MAY SIG = 5MV PP for 1MIL TRACK WIDE

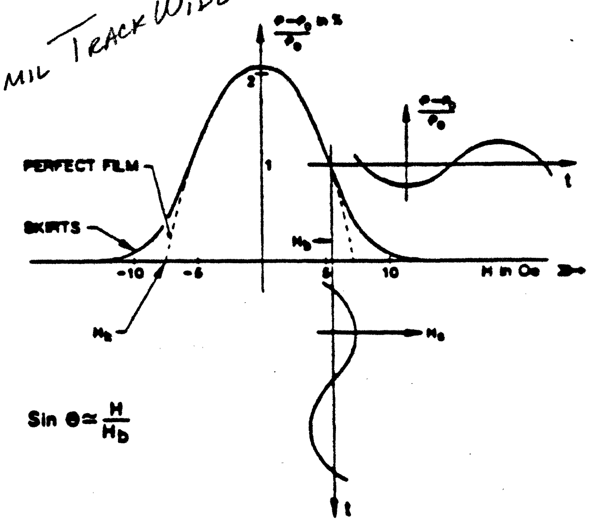


FIG. 29 SKETCH OF $\frac{\rho-\rho_0}{\rho_0}$ VERSUS H.

The element is subjected to a constant bias field Hb to move the operating point field to the inflection point in the curve to get maximum signal and minimum 2nd harmonic distortion. This generally corresponds to $\theta \doteq 45°$. Standard signal in/out versus time are shown in Fig. 29.

The resistivity ρ_0 of Permalloy is ~ 20-25 $\mu\Omega$cm, depending on thickness. $\Delta\rho$ is ~ 0.55$\mu\Omega$cm so $\Delta\rho/\rho_0 \doteq 2.5\%$. When the element is deposited on a high thermal conductivity substrate such as silicon or sapphire, current densities up to ~ $j \doteq 10^7$ amps/cm^2 can be handled. This corresponds to an internal electric field of $E = j\rho \doteq 200$ volts/cm. For an element length of 50μm (2 mils) the applied voltage V is a nominal 1 volt. The sensor temperature increase is ~ 20°C. Since the peak-to-peak $\Delta\rho/\rho_0$ is 2.5%, the maximum signal $S \doteq V\ \Delta\rho/\rho_0 \doteq 25$ mV. The nonlinearities shown in Fig. 29 limit the usable signal to about half this, or ~ 10 mV p-p for a 50μm element length. This is a very high signal level.

MR elements are fragile. They must be protected from burnout by electrostatic discharge and from damage by corrosion from finger prints, etc.

MR heads are typically classified in terms of how the bias field Hb is applied. Perhaps a dozen different bias techniques have been reported. These include external fields, adjacent hard and soft magnetic layers, shunt current in adjacent nonmagnetic layers, asymmetric placement of the sensor element in a magnetic gap, rotation of the current by "barber pole" conductor layers placed on the sensor layer, paired sensors each current biasing the other and "canted easy axis" (see Ref. 22 and others contained there). Bias has also been accomplished by exchange coupling between the MR element and an adjacent anti-ferromagnetic layer.[23] The mentioned biasing techniques are shown in Figs. 30 and 31. All but the external magnet in Figs. 30 and 31 are designed to provide the bias field inside the shields.

FIG. 30 MR HEAD BIAS TECHNIQUES

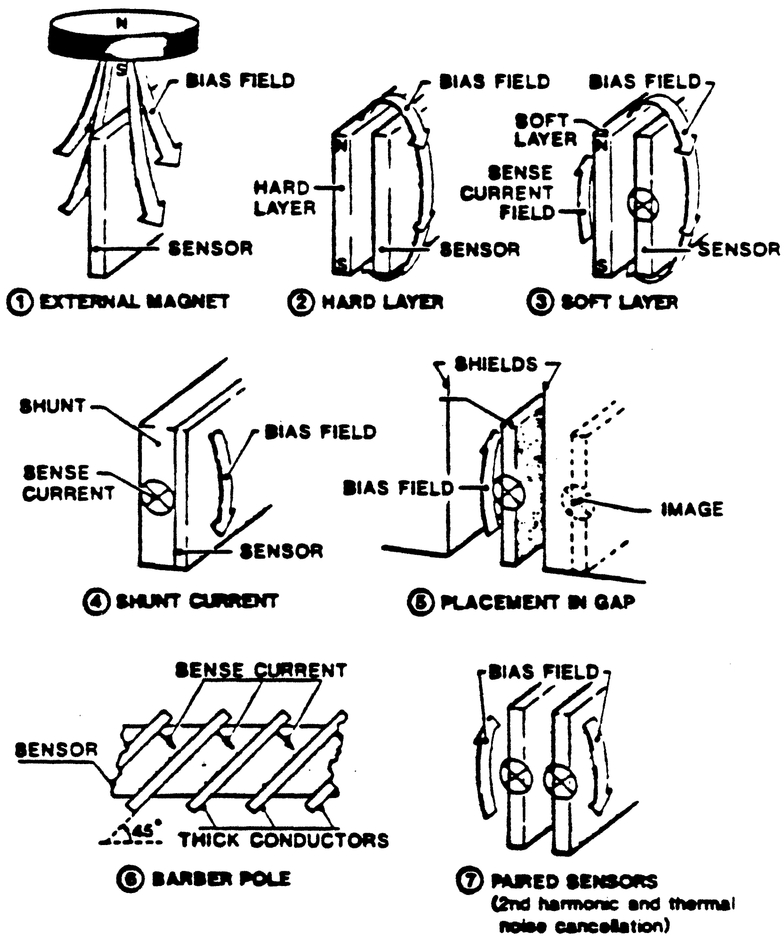
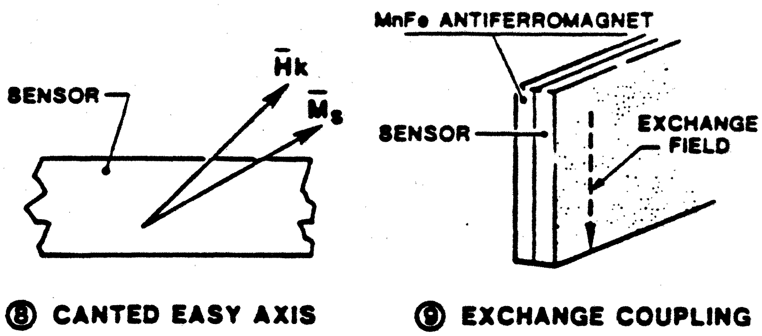
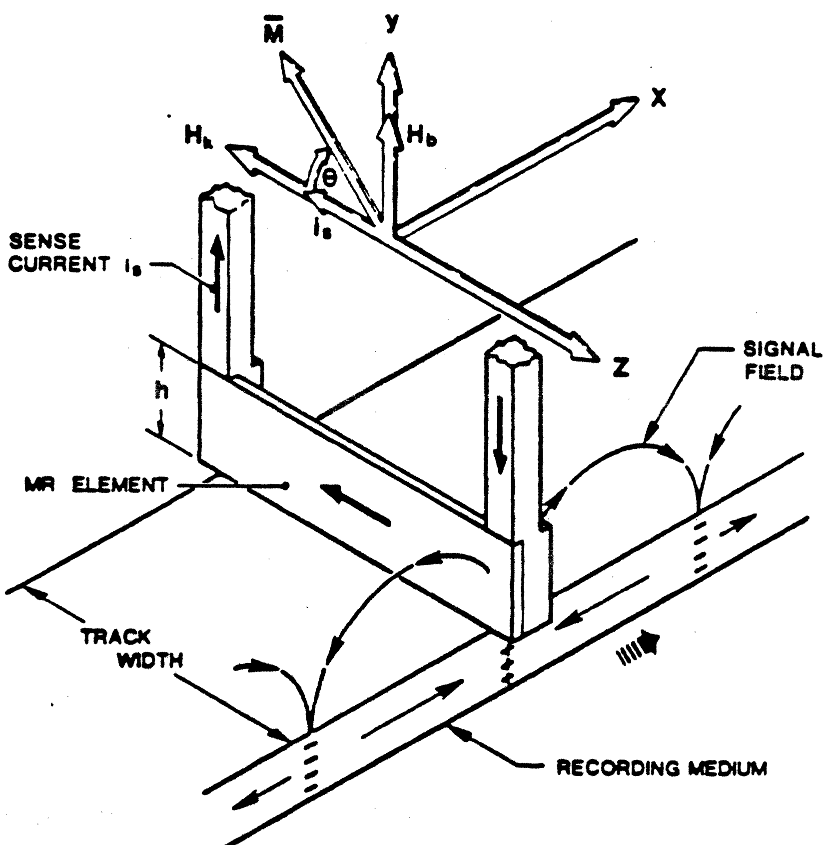


FIG. 31 (MR Heads Bias Techniques Cont.)



Discussion of all the above techniques is beyond the scope of this paper, but the simplest head developed by Hunt[24] is instructive. Figure 32 is a sketch of the Hunt head. It responds (semiquantitatively) to the vertical field above the media averaged over the element height h.

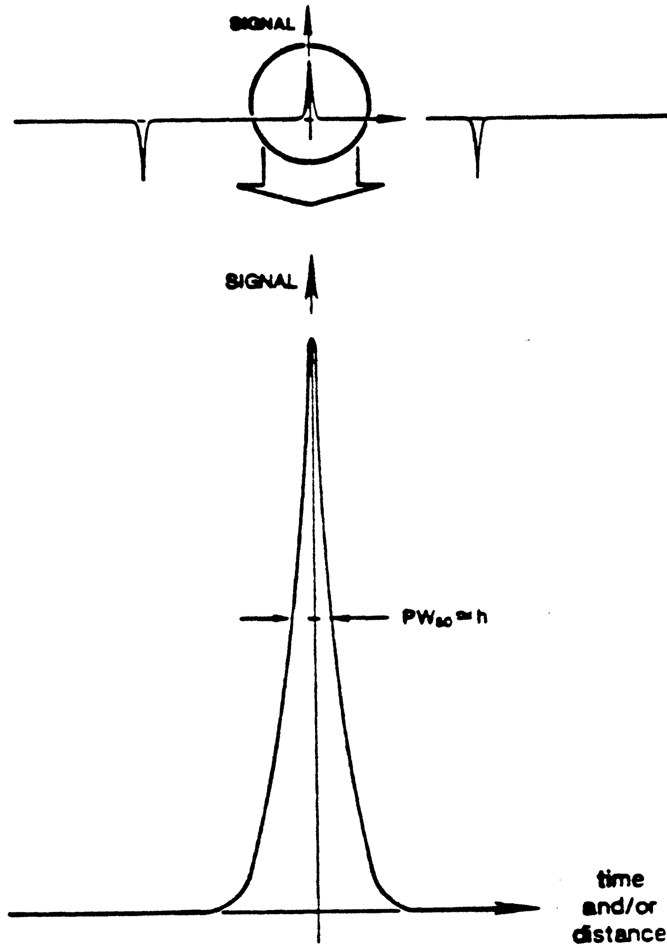
FIG. 32 UNSHIELDED MAGNETORESISTIVE HEAD



$$\rho = \rho_0 + \Delta\rho \cos^2 \theta$$

The height must be more than ~ 4-5μm or so, because of wear considerations. As a result, it detects approaching digital transitions before they are under the sensor. The isolated pulse shape is as shown in Fig. 33

FIG. 33 HUNT HEAD ISOLATED PULSE SHAPE



The full width at half maximum PW(50) = h for small head-medium separation. As a result, the signal spectrum covers a very large range as shown by Fig. 34, where spectra for several elements are shown.[25]

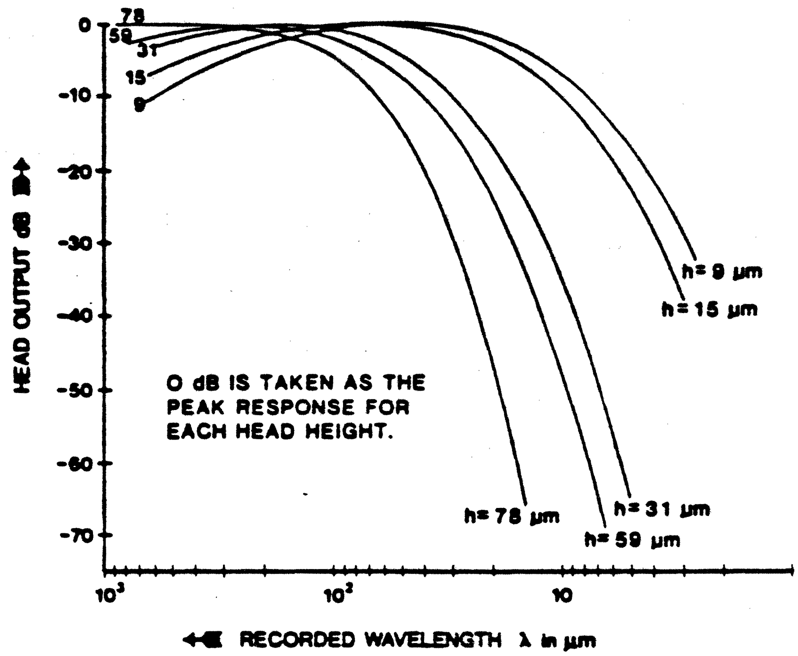


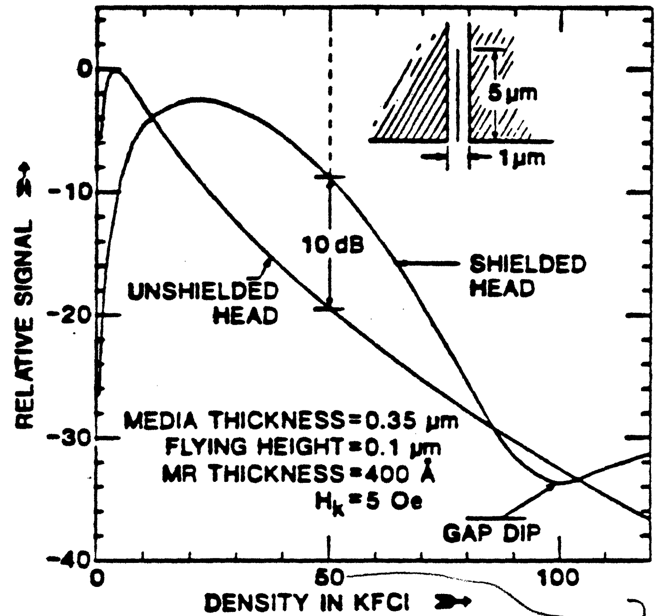
FIG. 34 FUNDAMENTAL FREQUENCY RESPONSES OF UNSHIELDED OPTIMALLY BIASED MR HEADS.

The peak-to-band-edge signal ratio, even for the h = 9μm head, is - 40 dB for a 2μm band edge wavelength.

This signal is relatively free of amplitude or phase nonlinearity and is equalizable. A paper was presented at the 1984 Intermag Conference describing the performance of a fully equalized unshielded MR head reproducing 80 kFCI data.[26] The peak-to-80-kFCI band-edge ratio for that head was 32 dB.

However, people have not wanted to equalize this much signal range so they put shields on either side of the MR element.[27] This greatly reduces the low density signal and actually increases the midband signal, so the peak-to-band-edge ratio is smaller. Putting on the shields also creates a "dip" at $\lambda \doteq g/2$, where g is the shield-to-shield gap.[28]

Figure 35 shows calculated response curves for otherwise identical unshielded and shielded heads.[29] Note that the midband signal of the shielded head is a maximum of 10 dB higher than that of the shielded head at 50 kFCI. At that density, $\lambda \approx g$.



$\lambda = 1\mu m$

FIG. 35 Comparison of shielded and unshielded MR head response curves.

Another type of MR head is called a "yoke MR" shown in Fig. 36. Here, the flux is collected by the yoke structure and conducted to the MR element, which is some distance removed from the media. The MR element is thus protected from the environment.

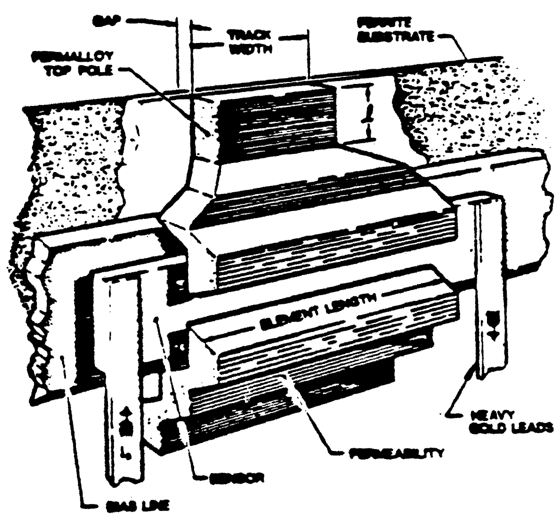


FIG. 36 YOKE MR HEAD
(Drawing not to scale)

Yoke MR heads have less signal than the Hunt head, but more signal than inductive heads at low media speeds. This is illustrated in Fig. 37 where yoke MR signal is plotted versus density. Also plotted is the output of a 200-turn inductive head, similar to that used ingenerating Figs. 4 and 19 at various tape speeds. As the tape speed increases, the signal advantage enjoyed by the MR head decreases. However, care must be taken to avoid resonance effects in inductive reproduce heads. The 200-turn head discussed here resonates at ~ 2 MHz, because of its relatively high inductance, unavoidable interwinding, and preamp capacitance.

MR head signal levels are extremely high. An inductive reproduce head would need ~ 4,000 turns to provide the same 100 kFCI signal as an unshielded Hunt head at 1 inch/sec medium speed. At a lower density of 10 kFCI, it would need 100,000 turns! Since MR head signal is independent of media speed, the signal advantage decreases as media speed increases but the maximum medium speed for an inductive head is limited by impedance noise and self-resonance effects. Because shielded or unshielded Hunt MR head signal is so high and its impedance is small and constant, its signal and signal-to-noise ratio is higher than a comparable trackwidth inductive head at any medium speed. This has been experimentally verified at speeds up to 230 inches/sec and densities as high as 100 kFCI.

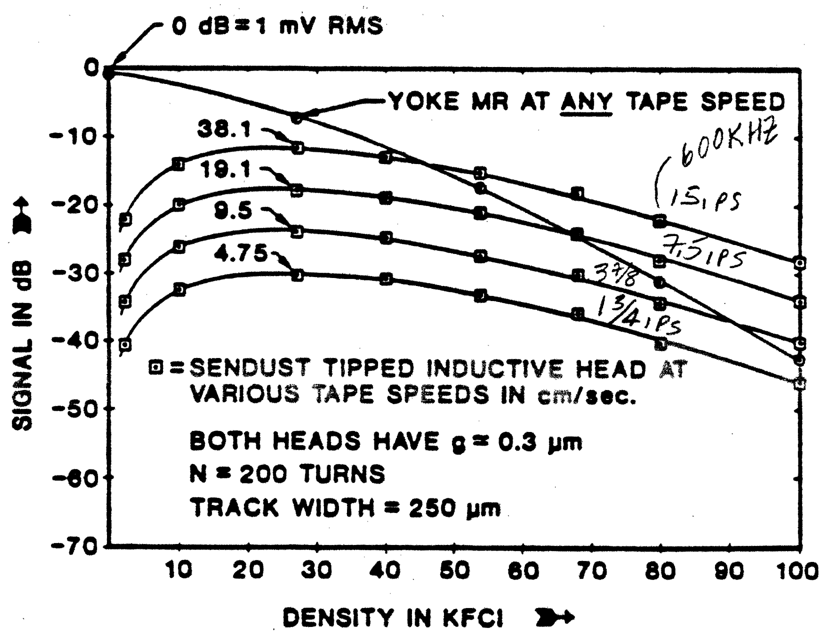


FIG. 37 YOKE MR & INDUCTIVE HEADS COMPARED

Another MR head worth noting is the recently described "over biased Hunt head" of Uchida.[30] Here, use is made of the fact that the demagnetization fields are greater at the edges of the sensor element. A bias field ~ 4 times larger than required for optimum signal is applied. This saturates the center of the element and causes the edge of the element in contact with the medium to be optimally biased. This reduces the short wavelength signal, but it reduces the long wavelength signal much more, giving improved resolution and a smaller peak-to-band-edge ratio, which is easier to equalize. The reduction in short λ signal is acceptable, as long as the medium noise remains larger than the electronic noise. This bias technique also results in some unavoidable second harmonic distortion which may result in unacceptable peak shift. MR heads have been combined with inductive thin-film record heads to form a complete read/write structure.[31]

Head Noise

There are many sources of noise in magnetic recording other than head noise, including record and reproduce crosstalk, signal modulation noise, overwrite, flutter and wow, and dropouts. The minimum tape noise is bulk erased noise which is easy to measure. The goal of the head designer is to cause the head noise to be less than the bulk erased noise, so that it does not affect the signal-to-noise ratio. The head is then said to give "tape-noise-limited performance".

The primary sources of inductive head noise are amplifier voltage noise E_V, amplifier current noise E_C, and head resistance noise E_r. E_V and E_C for a good wide band 40 dB gain amplifier are given by

$$E_V \simeq 1\times10^{-9}\,B^{1/2} \tag{21}$$

and

$$E_C \simeq 1\times10^{-12}\,B^{1/2}Z. \tag{22}$$

E_r is given by

$$\begin{aligned} E_r &\simeq (4k\,T\,B\,R)^{1/2} \\ &\simeq 1.29\times10^{-10}\,(B\,R)^{1/2}. \end{aligned} \tag{23}$$

B is the frequency bandwidth of concern in Hz, Z is the magnitude of the complex head impedance, k is Boltzmann's constant, $k = 1.38 \times 10^{-23}$ J/°K, T is the absolute temperature $T \cong 300$°C, and R is the real part of Z.

Figure 38 shows the "tape stopped" electronic noise spectrum for the 200-turn head discussed earlier. The bandwidth used was B = 3100 Hz. Vector impedance measurements were made of the head, which gave Z and R versus frequency, and E_v, E_c, and E_r were computed from Eqs. (21), (22), and (23). The inductance was about 745μH and the dc resistance was 16Ω. These results were also plotted in Fig. 38. The total expected electronic noise E_e was computed from

$$E_e = (E_v^2 + E_c^2 + E_r^2)^{1/2} \qquad (24)$$

E_e is also plotted in Fig. 38 and agrees very well with the tape stopped noise, except at very low frequency where recombination or 1/f noise from the amplifier and pickup noise become important.

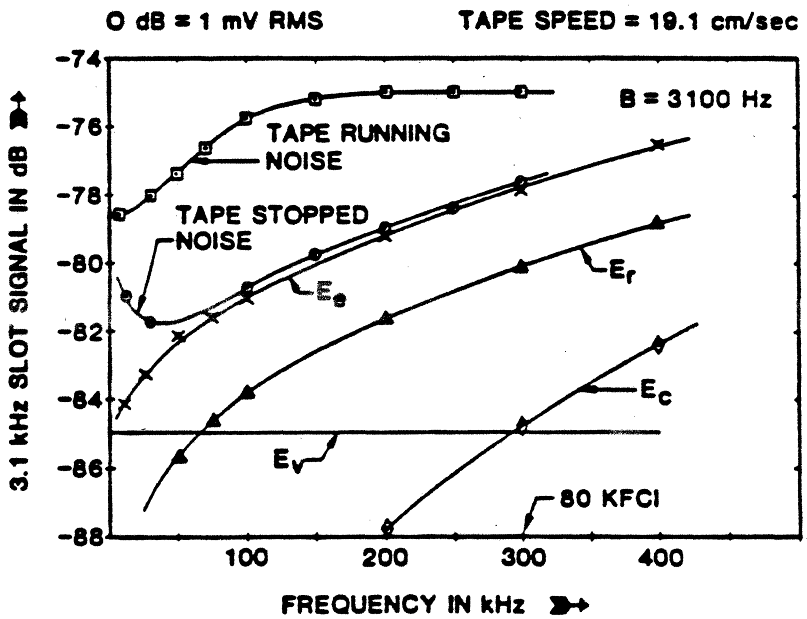


FIG. 38 INDUCTIVE HEAD NOISE SPECTRA

E_r increases with frequency primarily because of "eddy current resistance" in the conductive Sendust pole tips.

Finally, the bulk erased ISOMAX tape running noise is also plotted in Fig. 38. As can be seen, this head and tape make up a tape-noise-limited system, but with only 4 to 5 dB to spare. At higher top speeds, the margin is smaller because of the frequency-dependent head resistance.

Figure 39 shows the RMS to RMS, B = 3100 Hz slot signal-to-noise ratio for this Sendust tipped head and ISOMAX tape at 19.1 cm/sec tape speed. The record current was set to maximize the 80 kFCI signal.

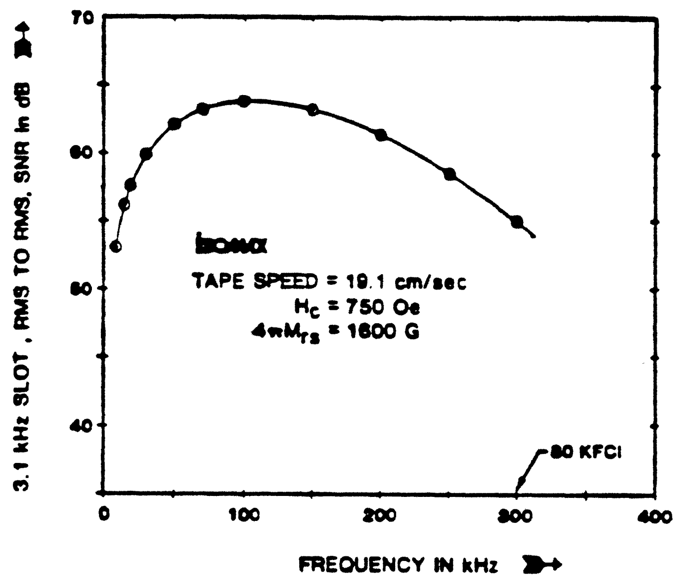


FIG. 39 3.1 kHz SLOT, RMS TO RMS, SIGNAL TO NOISE RATIO

In single-crystal ferrite heads, magnetostriction noise can be a problem. The choice of crystal orientation in the head is a compromise between permeability, wear rate and magnetostriction noise. The composition of the ferrite is chosen to minimize the magnetostriction constant, but a zero value is difficult to achieve at high saturation flux density which is required to avoid gap corner saturation.

The MR heads generate thermal noise. The temperature coefficient of resistance is - 0.28%/°C, so a 4°C temperature excursion gives a noise spike equal to the maximum signal of 1%! At 10^7 amps/cm², the sensor may be 20°C hotter than room temperature and the moving medium serves as a heat sink. Intermittent contact between head and medium, arising from poor medium surface smoothness or dust particles, causes thermal noise spikes as the element temperature goes up momentarily. This noise source is mostly confined to lower frequencies. Another source of thermal noise is frictional heating caused by hard dust or tape particles being dragged over the head surface. This is the dominate thermal noise at frequencies above the audio range. Even this noise source is confined to frequencies below ~ 250 KHz with a sapphire substrate.

Magnetostriction can also be a problem with MR heads. For these reasons, it is best to use a substrate like sapphire, which is very hard and has a high thermal conductivity to minimize thermal noise.

Barkhausen noise and even-order distortion associated with high flux levels in the MR layer can be a problem in some applications. Even-order distortion problems are minimized by using a truly run length-limited recording technique such as compact spectrum.[32] Magnetic feedback has been used to reduce the flux level in the Yoke MR element.[33] Barkhausen noise has been minimized by longitudinal exchange biasing.[34]

Several techniques have been developed to solve these and other MR head problems. See Refs. 21-22 and others therein. Figure 40 summarizes MR head noise sources.

FIG. 40 MR HEAD NOISE

a) THERMAL $\frac{d\rho}{dT} = 0.28\%/^\circ C$

$\Delta T = 4^\circ C \longrightarrow 1.2\% \; \Delta\rho$ = Max signal

Hard asperities sticking out of moving media surface cause frictional heating. Important below 200 KHz.

$\longrightarrow$ Need high thermal conductivity substrate like sapphire.

b) MAGNETO STRICTIVE

$\Delta H_k = \lambda \Delta S$ (λ: magnetostriction constant; S: strain)

So... $\Delta S \longrightarrow \Delta H_k \longrightarrow \Delta\sigma \longrightarrow \Delta\rho \longrightarrow$ noise.

$\longrightarrow$ Need $\lambda \longrightarrow 0$ (81/19 NiFe)

$\longrightarrow$ Need hard substrate like sapphire.

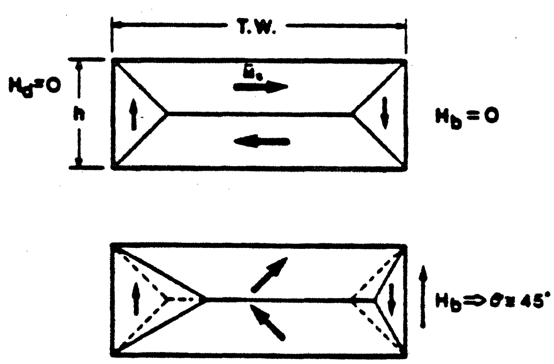
c) PIEZO RESISTIVE

$R = \frac{\rho \ell}{A}$ so... $\Delta S \longrightarrow \Delta\ell$ or $\Delta A \longrightarrow \Delta R \longrightarrow$ noise.

Need hard substrate.

d) BARKHAUSEN NOISE

Narrow T.W. $\Rightarrow$ Large $H_d \Rightarrow$ Domain Walls.



Large signal fields move domain walls at ends which "snap" over pinholes etc.

$\Rightarrow$ Barkhausen Noise

Generally not a problem for T.W. $\geq 50\mu$, $h \approx 5\mu$, $t \approx 700$ Å. Record Current set to max 80 KFCI $\Rightarrow$ Small Fields and contacts cover closure domains.

If approach bias point from high field side domain walls are mostly suppressed.

It has been shown that the standard Hunt MR head can achieve media-noise-limited performance at densities up to 60 kFCI with trackwidths as small as 4μm.[25] With a 4μm guard band, or 3200 tracks per inch, this corresponds to an areal storage density of nearly 200 MFC/in^2 which is equal to optical storage density!

SUMMARY

In order to achieve good high-density recording performance, the heads and media must be in intimate contact. The record gap must be as small as possible, but gap corner saturation must be avoided. This is difficult because high density media have high coercivity. The repro-duce gap must be small enough to avoid gap null loss, but large enough that adequate signal is obtained with a gap depth providing acceptable head life. Gap edges must be as straight and parallel as possible.

Vertical pole heads work well in recording on keepered vertical media, but not in reproduce because of a trade-off in gap loss and efficiency. The highest linear density has been achieved with unkeepered CoCr media and very small gap ring heads.

MR reproduce heads provide much higher signal levels than inductive heads, and they are easier to design to give media-noise-limited performance.

Primary inductive-head noise sources are resistance noise of the reproduce head, amplifier current noise, and amplifier voltage noise. Inductive reproduce systems can be media-noise limited, but it is difficult.

Principle MR head noise is scrape thermal noise caused by hard media asperities being dragged over the head surface and Barkhausen noise. Even-order distortion can be a problem. MR heads can achieve media-noise-limited performance at areal densities as high as 200 MFC/in^2.

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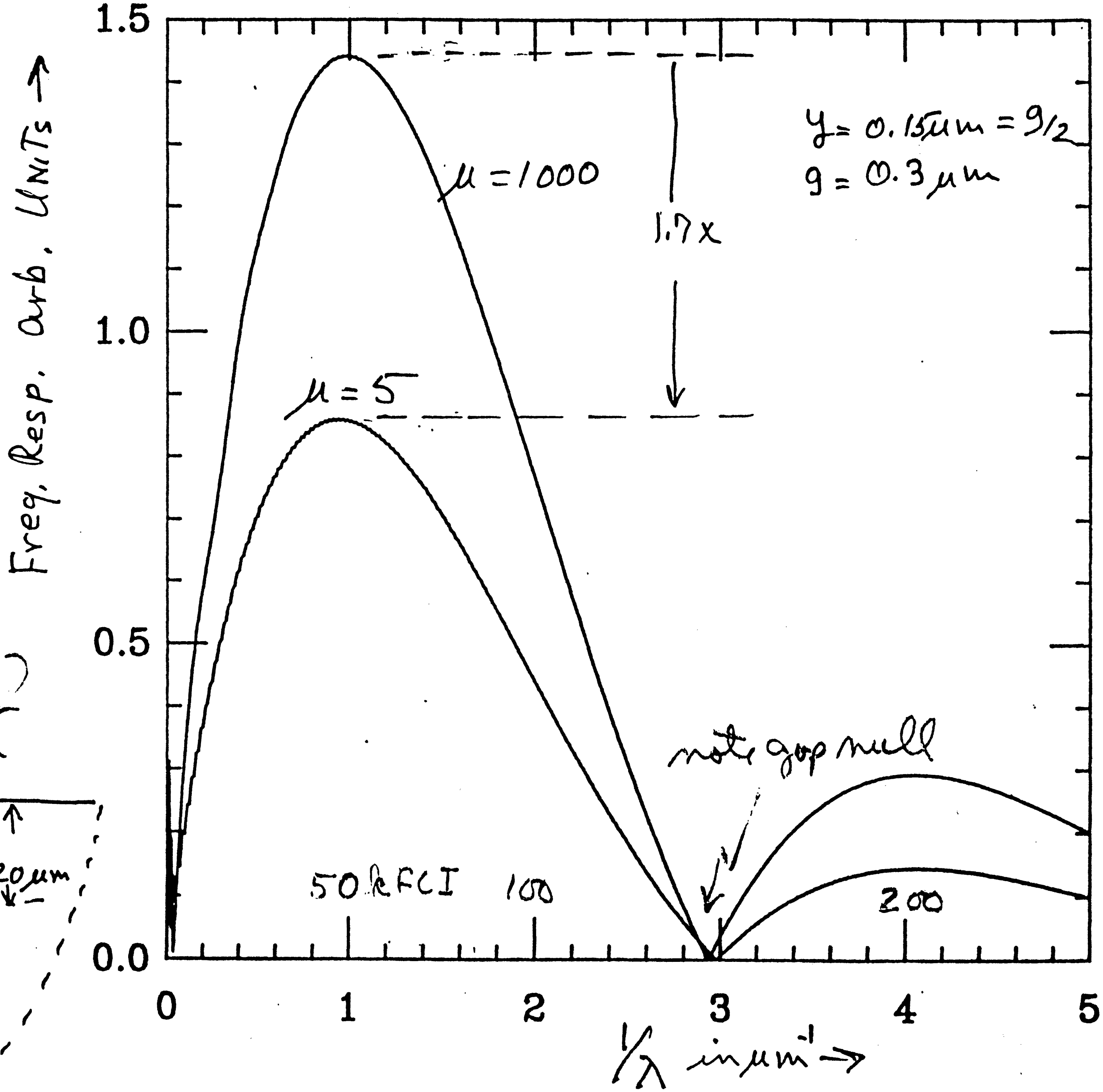
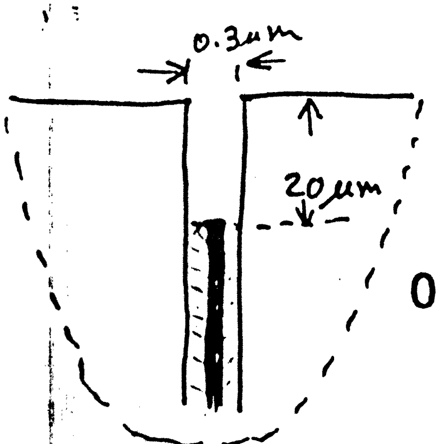
Signal spectra for all ones step transitions in a thin medium g/2 above a head with 2 permeabilities.



Courtesy of Neil Smith Kodak San Diego

head model



Back to Head Saturation

Normalized field gradient above a head with various permeabilities