CLASS NOTES

for

DASD

MAGNETIC CHANNEL

DESIGN

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DASD MAGNETIC CHANNEL DESIGN

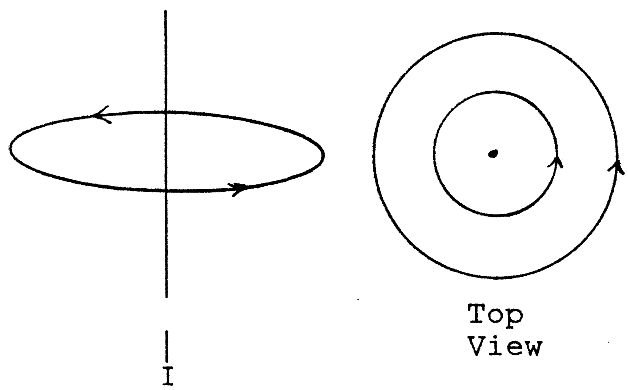
This course covers, from an integration point of view, the key components and processes of the recording and playback channel for rigid disk magnetic recording. The emphasis is on understanding the interaction of the magnetic and geometric parameters of heads and disks along with signal processing options for optimizing a design for desired bit and track densities and data and error rates. Included are: data encoding; the writing and reading processes on particulate and film disks, with ferrite, MIG, thin film, and magneto-resistive heads; signal and noise analyses, equalization, detection, and error correction.

COURSE OUTLINE:

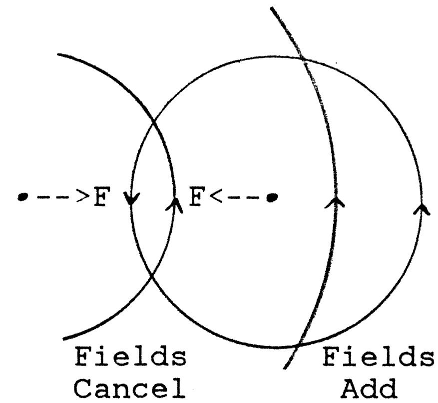
1. Review of Magnetics Fundamentals
2. Magnetic Units
3. Ferromagnetic Behavior
4. The Magnetic Transition
5. The Recording Head Field
6. The Write Process
7. The Read Process
8. Data Encoding, Detection and Error Correction
9. Noise Sources, SNR and Soft Error Rate
10. Equalization
11. Linear Density Design and Optimization
12. Track Density Design and Optimization

1. MAGNETIC FUNDAMENTALS

1.1 FORCE BETWEEN CURRENT CARRYING WIRES



Magnetic field around wire carrying dc current



2 Wires

Parallel wires with I in same direction attract, in opposite direction repel.

A magnetic field exerts a force on a current element.

A current element generates a magnetic field.

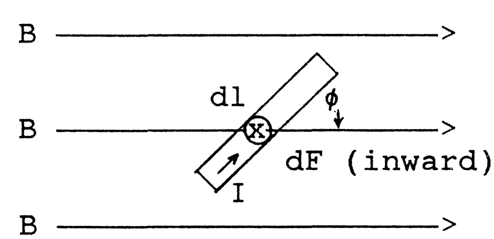
1.2 FORCE ON CURRENT ELEMENT

$dF = I \cdot dl \cdot B \cdot \sin\phi$ $F = I l B \sin\phi$

Force is perpendicular to plane

of **B** (FLUX DENSITY) and dl and ∞ sin of angle

between **B** and dl i.e. cross product



$$\vec{dF} = I(\vec{dl} \times \vec{B}) \tag{1.1}$$

1.3 FORCE PER CURRENT ELEMENT OR MAGNETIC FLUX DENSITY B

$I \cdot dl$ = Current X Length = **CURRENT MOMENT**

WITH $\phi = 90°$

$$\boxed{B \equiv \frac{dF}{I \cdot dl} = \frac{F}{I \cdot l} = \frac{\text{Force}}{\text{Current Moment}} \text{ or } \textbf{MAGNETIC FIELD INTENSITY}}$$

FLUX DENSITY

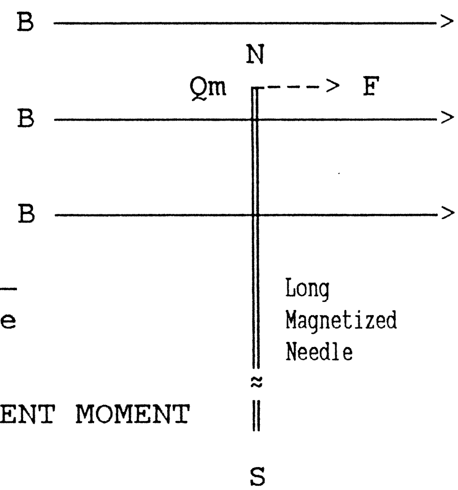
MAGNETIC CHARGE

Let Qm = pole strength of long magnet,

$$F = B \cdot Q_m \qquad = E \cdot Q$$

OR $\frac{\text{WEB-A}}{\text{M}} \quad \frac{\mu_0 \text{A}}{\text{M}} \text{ WEB} \qquad \frac{\text{VOLTS}}{\text{M}}, \text{ COUL}$

$$B = \frac{F}{Q_m} = \frac{\text{Force}}{\text{Pole Strength}} = \frac{\text{Force}}{\text{Unit Mag Pole}}$$



FOR EQUAL **B** AND **F**, POLE STRENGTH = CURRENT MOMENT

$$\boxed{\textbf{Unit Magnetic Pole = Unit Current Moment = 1 Amp-Meter}} \qquad (1.2)$$

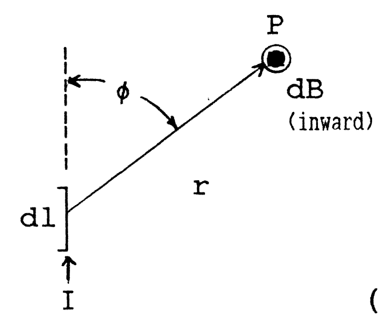
$$1 \text{ Unit of B} = \frac{\text{Unit Force}}{\text{Unit Mag Charge or Current Moment}} = \frac{1 \text{ Newton}}{\text{Amp-Meter}} = \frac{1\ \frac{\text{WEB-A}}{\text{M}}}{\text{A-M}} \qquad (1.3)$$

$$= \frac{1 \text{ WEB}}{\text{M}^2} = 1 \text{ TESLA}$$

This is a reactive definition. Let's examine a source of **B**.

1.4 B PRODUCED BY A CURRENT ELEMENT.

The field intensity produced at a point P by a current element I•dl is



$$dB = k \frac{I \cdot dl \cdot \text{Sin}\phi}{r^2} \qquad B = \frac{K I l \sin\phi}{r^2} \qquad (1.4)$$

k is a constant of proportionality given by

$$k = \frac{\mu}{4\pi} \qquad (1.5)$$

μ is the permeability of the medium.

The 4π is a matter of convenience since, as we will see, μ in air is defined with a 4π and, thus, the 4πs will cancel.

B can be thought of as lines of flux. the magnitude of **B** is the flux density or

NEWTON = WEB-A / M

$$\boxed{\mathbf{B} = \frac{\text{Webers}}{\text{meter}^2} \text{ also } = \frac{\text{Newtons}}{\text{Amp-meter}}} \tag{1.6}$$

B is called the **FLUX DENSITY** as well as the **MAGNETIC FIELD INTENSITY**.

(**B** is also called the magnetic induction and even sometimes the magnetic field...can be confusing).

From (1.5) it is seen that μ has the units of $\frac{\text{Weber}}{\text{Amp-Meter}}$

or since 1 amp through 1 Henry of inductance yields 1 webber of flux, 1 webber is 1 Amp-Henry. in vacuum or air

$$\boxed{\mu = \mu_o = \frac{4\pi}{10^7} \frac{\text{Weber}}{\text{Amp-meter}} \text{ OR } \frac{\text{Henry}}{\text{meter}}} \tag{1.7}$$

1.5 <u>AMPERE´S LAW AND H</u>

If (1.4) is solved for an infinitely long conductor,

$$B = \frac{\mu I}{2\pi R} \tag{1.8}$$

Where R is the perpendicular distance from point p to the conducting wire.

If **B** is integrated around a path of radius R enclosing the wire once, we have

$$\oint \mathbf{B} \cdot \mathbf{dl} = \mu I = 2\pi R B \tag{1.9}$$

The result is independent of R and holds for any path that encloses the conductor once.

Note that the integral has the units of force/unit charge x distance. This is the work required to move the pole of a long magnetized needle around a conductor carrying a current I.

Equation (1.9) can be made independent of the medium by introducing the quantity **H** where

$$\boxed{H = \frac{B}{\mu} \quad \frac{\text{Web/M}^2}{\text{Web/A-M}} \text{ OR } \frac{\text{Amperes}}{\text{Meter}}} \qquad \frac{WEB}{M^2} \cdot \frac{A\text{-}M}{WEB} = \frac{A}{M} \tag{1.10}$$

Ampere's Law is usually stated with H

$$\oint \mathbf{H} \cdot d\mathbf{l} = \mathbf{I} \tag{1.11}$$

H is commonly called the magnetic field. This name is misleading since it implies that **H** is analogous to the electric field **E** which is not the case since in electric fields **E** enters into the force relation, where as in magnetic fields it is **B** that enters in the force relation. The name "**Magnetizing Force**" is more descriptive of **H**.

1.6 B PRODUCED BY A CURRENT LOOP

The Field Intensity, **B**, on the axis of a closed current loop is

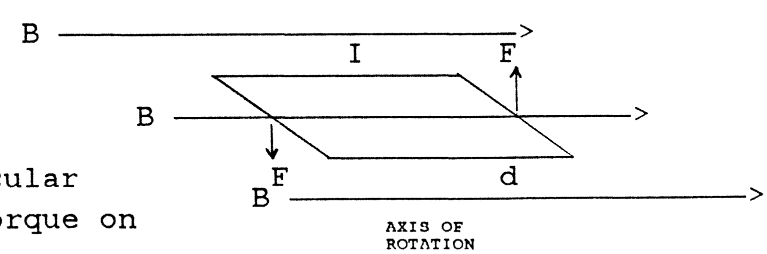
$$B = \frac{\mu I}{2R} \tag{1.12}$$

Note that **B** is inversely proportional to the radius r of the loop and the difference between this and (1.8) is a factor π.

1.7 MAGNETIC MOMENT

When a current loop is place in a field **B** with its plane parallel to **B**, the resulting force tends to rotate the loop about an axis perpendicular to the field. For simplicity consider a square loop of side d.

The only force is on the sides is perpendicular to the field. From (1.1) the force on each perpendicular side is I•d•B. the torque on the loop is



TURNS

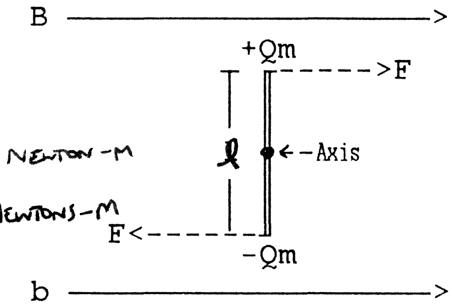
$$\mathbf{T = 2 \cdot F \cdot d/2 = I \cdot d^2 \cdot B = I \cdot A \cdot B} \qquad T = I d^2 B n = I \cdot A \cdot B \cdot n \tag{1.13}$$

$F = I \cdot d \cdot B \qquad B = \frac{F}{I \cdot d}$

A is the area of the loop and is independent of the shape.
The product **I·A** is the magnetic moment of the loop

$$\mathbf{m} = \mathbf{I \cdot A} \quad \text{Amp-Meter}^2 \quad \text{Also} = \mu_o \cdot I \cdot A \ \text{Weber-Meter} \tag{1.14}$$

small **m** is used for magnetic moment. large **M**, yet to be introduced, will be called magnetization.



If a short magnetic bar is placed in a field of intensity **B**, the torque is

A-m · $\frac{\text{WEB}}{m^2}$ = A-WEB = NEWTON-M

$$T = 2Qm \cdot B \cdot \ell/2 = Qm \cdot \ell \cdot B = \frac{\text{NEWTON}}{\text{A-m}} \cdot \text{A-M} = \text{NEWTONS-M}$$

Equating torques of a loop and bar we get

$$T = I \cdot A \cdot B = Q_M \cdot \ell \cdot B$$

$$I \cdot A = Q_M \cdot \ell$$

$$\underset{\text{A-M}^2}{\mathbf{m} = \mathbf{I \cdot A}} = Qm \cdot \ell \leftarrow \text{A-M}^2 \qquad T = M \times H = Q_M \cdot B \ \text{OUTSIDE (IN AIR)} \tag{1.15}$$

$$= |M| \cdot |H| \sin\theta$$

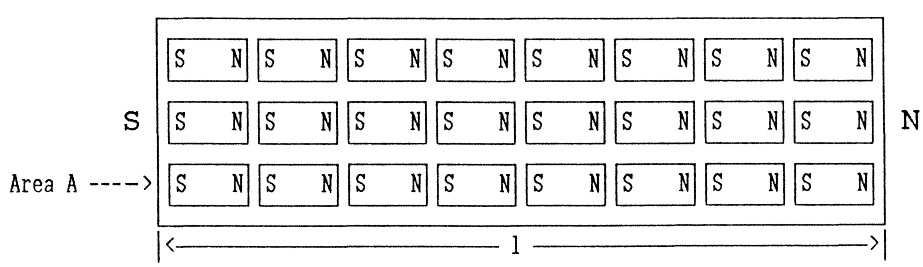
The product $Qm \cdot \ell$ is also known as the **MAGNETIC DIPOLE MOMENT.**

The fields at a distance from a CURRENT LOOP and a BAR MAGNET are identical if the magnetic moments are equal.

There is an magnetic equivalence between a round bar magnet and a solenoid if the solenoid current is chosen properly.

1.8 MAGNETIC DIPOLES AND MAGNETIZATION

A magnetized rod can be thought of as being made up of many little magnetic dipoles (or current loops) of **m**.



The magnetization **M** of the rod is defined as the dipole moment per unit volume.

If each little dipole has a charge qm and length dl,

$$M = \frac{m}{V} = \frac{1}{V}\iint qm \cdot dA \cdot dl = \frac{Qm \cdot \ell}{\underset{\text{volume}}{V}} = \frac{Q_m \cdot \ell}{\text{Area}\ \ell} = \frac{Q_m}{\text{Area}} \quad \frac{\text{AMPS}}{\text{METER}}$$

If the volume V is A•l

$$M = \frac{Qm \cdot \ell}{A \cdot \ell} = \frac{Qm}{A} \quad \frac{\text{Amp-Meter}}{\text{Meter}^2} \text{ OR } \frac{\text{Amps}}{\text{Meter}} \tag{1.16}$$

The magnetized rod can also be thought of as being made up of current loops distributed along its length, at its surface (like a solenoid).

From (1.15), (1.16) can also be written as

$$M = \frac{m}{V} = \frac{Qm \cdot \ell}{V} = \frac{NI \cdot A}{V} = \frac{NI \cdot A}{A \cdot \ell} = \frac{NI}{\ell} \quad \frac{\text{Amps}}{\text{Meter}}$$

NI/ℓ is the number current loops/unit length each carrying a current I.

A MAGNETIZED ROD CAN BE REPRESENTED EQUALLY WELL AS BEING MADE UP OF MANY DIPOLES DISTRIBUTED THOUGH OUT ITS VOLUME, BY MAGNETIC CHARGE DISTRIBUTED OVER ITS ENDS OR BY CIRCUMFERENTIAL CURRENT LOOPS DISTRIBUTED ALONG ITS LENGTH. THE UNITS IN EACH CASE ARE AMPS/METER, THE SAME AS H.

$$\mathbf{M} = \frac{\mathbf{Qm \cdot \ell}}{\mathbf{V}} = \frac{\mathbf{Qm}}{\mathbf{A}} = \frac{\mathbf{NI}}{\boldsymbol{\ell}} \quad \frac{\mathbf{AMPS}}{\mathbf{METER}} \tag{1.17}$$

The different representations are useful for different considerations. This can seem confusing unless the equality is kept in mind.

Magnetization is one of the primary parameters that characterize a magnetic material. It is often referred to as the moment...another source of confusion.

1.9 THE MAGNETIC VECTORS B, H, AND M

From equation (1.10) we have for the general case

$H = B/\mu$ AND $B = \mu \cdot H$

In nonferromagnetic media

$H = B/\mu_o$ and $B = \mu_o \cdot H$

In ferromagnetic media the difference in μ is due to the magnetization **M**.

MAGNETIC FIELD
FLUX DENSITY
MAGNETIZATION

$$\mathbf{H} = \mathbf{B}/\mu_o - \mathbf{M} \quad \text{and} \tag{1.18}$$

$$\mathbf{B} = \mu_o(\mathbf{H} + \mathbf{M}) \tag{1.19}$$

Thinking in terms of the ´magnetic charge at the poles representation´, **M** generates magnetic charges at the poles of the media and the charge in turn generates the **H** and **B** fields.

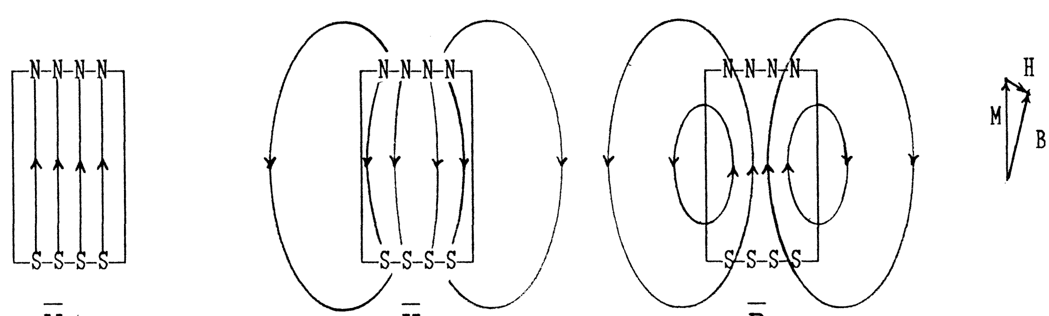
Lines of **M** start and end on the magnetic charges and lie inside the media.

Lines of **H** start and end on the same magnetic charges and lie both in and out of the media but with different densities or magnitudes.

Lines of **B** are continuous inside and outside the media. Inside the media **M** and **H** are in the opposite direction.

H inside the media that is in response to **M** is called the demagetizing field since it opposes **M**.

As seen from equation (1.21) if μ_r is much greater than 1, the magnitude of **H** inside the media is small.



$\overline{M}$ INSIDE $\overline{H}$ OUTSIDE $\overline{B}$

Equation (1.19) can be written as

$$B = \mu_o(H + M) = \mu_o(1 + M/H)\cdot H = \mu_o\,\mu_r H$$

$\mu_o \cdot \mu_r = \mu$ and

$\mu_r = 1 + M/H$ is the **Relative Permeability.** (1.20)

μ_r is in general very large in ferromagnetic materials ranging from 600 for nickel to 100,000 for permalloy and 200,00 for pure iron.

Thus within in magnetized ferromagnetic material **M** » **H** and

$$B = \mu_o \cdot M. \tag{1.21}$$

The magnitude of the demagnetizing field, **H**, arising from the magnetic charges is proportional to **M** and is governed by the inverse square law.

Thus ~~it~~ H decreases rapidly within the media.

For our purposes demagnetization will only be of significance when concidering media of high **Mr** and close pole, or transition, spacing (i.e. thin film media at high linear density).

The **B**, **H** and **M** vectors have a number of interesting vector relationships involving divergence, gradient and curl that are used to advantage in a more rigorous treatment (See chapter 4 of Kraus.) but are not needed for our purposes.

References:

1. Kraus, J. D., Electro-Magnetics, McGraw-Hill, New York, 1953

2. Mee, C. D., Magnetic Recording Vol 1 McGraw-Hill, New Youk, 1985

3. Mallinson, J. C., The Foundations of Magnetic Recording, Academic Press, San Diego, 1987

Problem 1.1

A linear conductor carries a current of 10 amps in the + x direction. If the flux density everywhere is uniform with a magnitude of B = 2 Weber/meter^2 parallel to the x-y plane and at an angle 45 degrees with respect to the x axis, find the magnitude and direction of the force on a 2 meter length of the conductor.

$F = I \ell B \sin\phi$

Problem 1.2

A thin linear conduction situated in air carries a current of 10 amps. What is the flux density produced by a section of the conductor 1 cm long at a distance of 2 meters normal to the 1 cm section? What is the H field?

$B = \frac{\mu_0}{4\pi} \frac{I \cancel{\phi} \ell \sin\phi}{r^2} =$

Problem 1.3

Starting with equation (1.4) show that the field or flux density B at a point a distance R from an infinitely long wire carrying a current I is:

$$B = \frac{\mu_0 \cdot I}{2\pi \cdot R}$$

$\sin\theta = \cancel{\frac{d\ell}{R}}$ $\quad d\ell = R\sin\theta d\theta$

$\sin\theta = \frac{R}{d\ell}$ $\quad d\ell = \frac{R}{\sin\theta}$

(hint: try letting the variable of integration be $d\phi$.)

Problem 1.4

What is the flux density for the conditions of problem 2 due to an infinite length of the conductor?

Problem 1.5

A uniform magnetic dipole moment of 80 amp-meter^2 is generated in a bar with a volume of 1,000 cm^3 and μ_r of 1000 when it is placed in a uniform magnetic field of B. Find M, H, and B.

$M = \frac{m}{V}$ $\quad \mu_r = 1000$

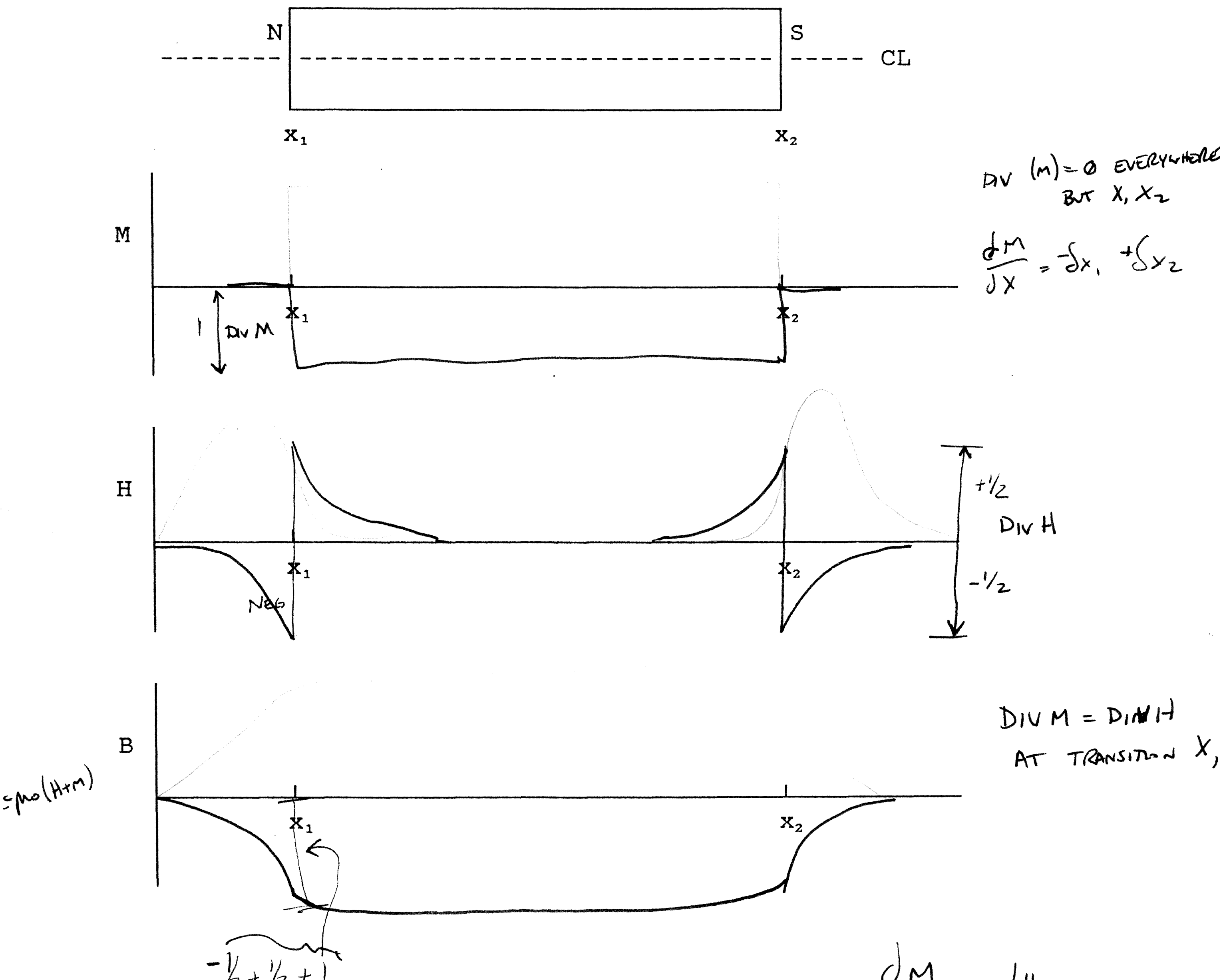
$\mu_r = 1 + M/H$

Problem 1.6

What is the maximum torque on a small, square loop of 100 turns in a field of uniform flux density of B = 3 Weber/meter^2? The loop is 10 cm on a side and carries a current of 1 amps. (b) What is the magnetic moment of the loop?

Problem 1.7

For a bar of maginetic material sketch the magnitude of the **M, H** and **B** fields along the center line. Let the X axis be parallel to the center line.



$$\frac{\partial M}{\partial x} + \frac{\partial H}{\partial x} = \emptyset$$

$$\frac{\partial M}{\partial x} + \frac{\partial H}{\partial x} = \emptyset$$

$$\frac{\partial M + \partial H}{\partial x} = \emptyset \qquad \frac{\partial M}{\partial x} = \frac{-\partial}{\partial}$$

2. MAGNETIC UNITS EQUIVALENTS AND CONVERSIONS

There are several factors that lead to confusion between the MKS and CGS magnetic units.

There is confussion within each system.

There is not a one for one units correspondance in the quanties. For example the basic unit of magnetic charge in MKS is the A-m while in the CGS it is EMU/cm -- a length^2 difference.

Each system has two quantities commonly used for magnetic charge.

The EMU/cm emits 4π lines of flux, Gauss, while the A-m emits $4\pi \cdot 10^{-7}$ lines of flux, Tesla.

μ_0 in MKS is $4\pi/10^7$ while in CGS it is 1.

Converting with unfamilar units can often be confussing. For example. How the conversion is stated is key.

1 foot = 12 inches however
L in feet = L in inches/12

The difference is whether you are stating a converson equivalency or converting a given numerical value.

In the former case the numerical values are different since the units are different.

In the latter case the numerical values are equal since the conversion is being made.

2.1 MAGNETIC CHARGE

Force is a good linking point between MKS and CGS-EMU systems.

In MKS there are two forms of the force equation often encountered.

$$F_M = \frac{\mu_{o\,m} (Qm_{M\,1})^2}{4\pi \cdot d^2} = \frac{(Qm_{M\,2})^2}{\mu_{o\,m} 4\pi \cdot d^2}$$

The $_M$ subscript denotes MKS units.

F_M is in Newtons

$Qm_{M\,2} = Qm_{M\,1} \cdot \mu_o = Qm_{M\,1} \cdot 4\pi \cdot 10^{-7}$

$Qm_{M\,2}$ is in Webers (Web)

$Qm_{M\,1}$ is in Amp-meters (A-m)

$\mu_{o\,M}$ is in Web/A-m or Henry/meter = $4\pi/10^7$ $\frac{\text{WEB}}{\text{A-M}}$

d is in meters

$$\begin{array}{cccc} & \textbf{(A-m)} & & \textbf{(Web)} \\ \mathbf{F_M \text{ in Newtons}} = & \dfrac{\mu_{o\,m} (Qm_{M\,1})^2}{4\pi \cdot d^2} & = & \dfrac{(Qm_{M\,2})^2}{4\pi \cdot \mu_{o\,m} \cdot d^2} \end{array} \qquad (2.1)$$

$\frac{W}{A-M} \frac{(A-M)^2}{M^2} = \frac{WA}{M}$ $\frac{(W)^2}{W} \frac{A-M}{M^2} \frac{WEB}{} = \frac{WA}{M}$ = NEWTONS

It does not matter which we use as long as we use the correct Qm.

In the strictest sense A-m is the perfered unit of charge and emits μ_o Webers of flux; however, it is easy to equate one unit of flux to one unit of charge. Thus arises the Weber form.

Also the Weber form is analogous to the electrostatic equation for force in that μ_o like e_o is in the demominator.

In CGS units there are, similarly, two forms that can be used.

$$F_c \text{ in Dynes} = \underset{(\text{EMU/cm})}{\frac{(Qm_{c\,1})^2}{\mu_{o\,c}\cdot d^2}} = \underset{(\text{Max})}{\frac{(Qm_{c\,2})^2}{(4\pi)^2\cdot\mu_{o\,c}\cdot d^2}} \qquad 4\pi\,\frac{MAX^2}{CM^2}\cdot\frac{OE}{GA} \tag{2.2}$$

$$= 4\pi\,\frac{MAX^2}{CM^2}\;\frac{OE}{1\;MAX/CM^2}$$

$$= 4\pi\;MAX\;OE$$

$$4\pi\;10^{-8}\;WEB\;\frac{10^3}{4\pi}\;A/M$$

$$= 10^{-5}\;\frac{WEB\text{-}A}{M} = 10^{-5}\,NEWTON = 1\;DYNE$$

The subscript $_c$ denotes CGS.

$Qm_{c\,1}$ is in EMU/cm

$Qm_{c\,2}$ is in Maxwells (Max)

$Qm_{c\,1} = Qm_{c\,2}/4\pi$

$\mu_{o\,c}$ is Gauss/Oersted (Ga/Oe) $\equiv 1$

d is in cm

The prefered unit charge is the EMU/cm which emits 4π Maxwells of flux.

The Maxwell form is seldom used but is useful in starting the the conversion process.

Note that there is a factor of length^2 difference between the unit of magnetic charge in the two systems, i.e A-m and EMU/cm. The definition of EMU will be given in section 2.5.

In order to find the conversion factors for Qm between the two systems consider two magnetic charges separated by 1 meter.

```
Qm                                Qm
 •<-------- 1 m -------->•
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The force between the charges, calculated in each system is related by

$F_c = F_M \cdot 10^5$ since there are 10^5 dynes/Newton.

$$F_c = \underset{(\text{EMU/cm})}{\frac{(Qm_{c\,1})^2}{\mu_{o\,c}\cdot d^2}} = \underset{(\text{Max})}{\frac{(Qm_{c\,2})^2}{(4\pi)^2\cdot\mu_{o\,c}\cdot d^2}} \qquad \frac{EMU^2}{CM^2}\cdot\frac{\cancel{GA}\,OE}{GA}\cdot\frac{1}{CM^2}$$

$$F_M(10^5) = \underset{(\text{A-m})}{\frac{\mu_{o\,m}(Qm_{M\,1})^2}{4\pi\cdot d^2}}\cdot(10^5) = \underset{(\text{Web})}{\frac{(Qm_{M\,2})^2}{4\pi\cdot\mu_{o\,m}\cdot d^2}}\cdot(10^5)$$

Substituting $\mu_{o\,M} = 4\pi/10^7$, $\mu_{o\,c} = 1$, $d_M = 1$ & $d_c = 100$

$$\underset{\text{(EMU/cm)}}{\frac{(Qm_{c\,1})^2}{10^4}} = \underset{\text{(Max)}}{\frac{(Qm_{c\,2})^2}{(4\pi)^2 \cdot 10^4}} = \underset{\text{(A-m)}}{\frac{(Qm_{M\,1})^2}{10^7} \cdot (10^5)} = \underset{\text{(Web)}}{\frac{(Qm_{M\,2})^2}{(4\pi)^2} \cdot (10^{12})}$$

Multiplying through by 10^4 and taking the square root

$$\underset{\text{(EMU/cm)}}{Qm_{c\,1}} = \underset{\text{(Max)}}{\frac{Qm_{c\,2}}{4\pi}} = \underset{\text{(A-m)}}{Qm_{M\,1} \cdot 10} = \underset{\text{(Web)}}{\frac{Qm_{M\,2}}{4\pi} \cdot 10^8} \tag{2.3}$$

Thus

$$\boxed{\mathbf{1\ EMU/cm = 10^{-1}\,A\text{-}m = 4\pi \cdot 10^{-8}\,Web}} \tag{2.4}$$

and

$$\boxed{\mathbf{1\ Maxwell = 10^{-8}\,Weber = 1/(4\pi 10)\ A\text{-}m}} \tag{2.5}$$

Also

$$\boxed{\begin{array}{l} \mathbf{1\ EMU/cm = 4\pi\ Maxwell} \\ \mathbf{1\ A\text{-}m = 4\pi/\mu_o\ Weber} \end{array}} \tag{2.6}$$

2.2 FLUX DENSITY, B

B_M is in $Web/M^2 \equiv$ Tesla

B_c is in $Max/cm^2 \equiv$ Gauss

$$B_c/B_M = \frac{Max/cm^2}{Web/m^2} = \frac{Max}{Web} \cdot \frac{M^2}{cm^2} = 10^{-8} \cdot 10^4 = 10^{-4}$$

$$B_c = B_M \cdot 10^{-4}$$

$$\boxed{\mathbf{1\ Gauss = 10^{-4}\ Tesla}} \tag{2.7}$$

2.3 MAGNETIC FIELD, H

$$H_M = B_M/\mu_{oM} = \text{Amp/meter}$$

$$H_C = B_C/\mu_{oC} = \text{Oersted}$$

$$H_M/H_C = \frac{B_M}{B_C}\cdot\frac{\mu_{oC}}{\mu_{oM}} = 10^{-4}\cdot\frac{10^7}{4\pi} = \frac{10^3}{4\pi}$$

$$H_C = H_M\cdot\frac{10^3}{4\pi}$$

$$\boxed{1\ \text{Oe} = \frac{10^3}{4\pi}\ \frac{\text{Amp}}{\text{meter}}} \qquad (2.8)$$

2.4 CURRENT, I

Ampere's Law

$$\int H dl = I$$

$$H_M\cdot l_M = I_M$$

l_M is in meters

I_M is in Amperes

$$H_C\cdot l_C = I_C$$

l_C is in cm

I_C is to be determined

$$I_M/I_C = \frac{H_C}{H_M}\cdot\frac{l_C}{l_M} = \frac{10^3}{4\pi}\cdot\frac{1}{100} = \frac{10}{4\pi}$$

$$I_M = \frac{10}{4\pi}\cdot I_C$$

One unit of $I_C \equiv 1$ Gilbert

$$\boxed{1\ \text{Gilbert} = \frac{10}{4\pi}\ \text{Ampere}} \qquad (2.9)$$

Generally the current is converted to Amperes in the CGS-EMU system.

2.5 MAGNETIC DIPOLE MOMENT, m

Since dipole moment is $Qm \cdot \ell$, we can creat equal moments by multiplying the equal charges of equations (2.4) and (2.5) by equal lengths of 1 cm or .01 m as appropriate.

Thus

$$\boxed{1 \text{ EMU} = 10^{-3} \text{A-m}^2 = 4\pi \cdot 10^{-10} \text{Web-m}} \tag{2.10}$$

and

$$\boxed{1 \text{ Maxwell-cm} = \frac{10^{-3}}{4\pi} \text{A-m}^2 = 10^{-10} \text{Weber-m}} \tag{2.11}$$

Also

$$\boxed{\begin{array}{l} 1 \text{ EMU} = 4\pi \text{ Maxwell-cm} \\ 1 \text{ A-m}^2 = 1/\mu_{o\,M} \text{ Web-m} \end{array}} \tag{2.12}$$

The MKS equation of (2.11) reflects the equivalent repersentations of current times area and charge times length for magnetic moment as discussed in section 1.7. This equivalency is not so evident in the CGS case.

The EMU and the A-m^2 are the perferred units.

The system that is popular in much of the magnetics industry and US literature uses EMUs for magnetic moment, **m**, and magnetization, **M**, together with Gauss for flux density and field, **B**, and Oersted for magnetizing force, **H**.

2.6 MAGNETIZATION, M

Since **M** is moment **m** per unit volume, we can creat equal magnetizations by dividing equations (2.9) and (2.10) by equal volumes of 1 cm^3 and 10^{-6} $meter^3$.

Thus

$$\boxed{1\ \mathbf{EMU/cm^3} = \mathbf{10^3\,A/m}} \boxed{\Rightarrow\ \mathbf{4\pi \cdot 10^{-4} Web/m^2}} \qquad (2.13)$$

and

$$\boxed{\mathbf{1\ Maxwell/cm^2 \Leftarrow\ 10^3/4\pi\ A/m \Rightarrow\ 10^{-4} Weber/m^2}} \qquad (2.14)$$

Also

$$\boxed{\begin{array}{l} \mathbf{1\ EMU/cm^3 \Rightarrow 4\pi\ Maxwell/cm^2 = 4\pi\ Gauss} \\ \quad \mathbf{1\ A/m \Rightarrow 1/\mu_{o\,M} Web/m^2} \end{array}} \qquad (2.15)$$

Although quations (2.9, 10 & 11) express equal quantities some distinctions must be made.

In MKS **A/m or A-m/m²** are used for the magneization **M**.

$\mu_{o\,M} \cdot M$ is Web/m² but is the flux density **B** emitted by **M**. See equation (1.21)

In CGS **EMU/cm³** is used for magnetization (often called moment).

Gauss is the flux density emitted by **M**.

Since

$$\mu_{o\,c} = 1\ \frac{\text{Oersted}}{\text{Gauss}} = 1$$

there is a numerical equivalancy between Gauss and Oersted in CGS units that leads to **B** and **H** being used interchangably and the difference can become blurred.

$$1\ \text{EMU/cm}^3 = 4\pi\ \text{Gauss} = 4\pi\ \text{Oersted}$$

The magnetization **M** is sometimes expressed as Oersted.

$$\frac{M_C}{M_M} = \frac{\text{Oersted}}{\text{Amp/Meter}} = \frac{10^3}{4\pi}$$

$$\boxed{\begin{array}{l} \mathbf{1\ M_C\ Oersted} = \dfrac{10^3}{4\pi}\cdot \mathbf{M_M\ Amp/meter} \\ \mathbf{or} \\ \mathbf{1\ Oersted} = \mathbf{4\pi/10^3\ Amp/meter} \end{array}} \qquad (2.16)$$

THE FIELD FROM A MAGNETIZED FERROMAGNETIC MEDIA IS **4πM** GAUSS WHEN **M** IS EMU/CM^3 ; WHEREAS, IT IS JUST **M** GAUSS WHEN **M** IS OERSTED.

$$1\ M_C\ \text{Oersted} = \frac{1}{4\pi}\frac{\text{EMU}}{\text{cm}^3} = \frac{10^3}{4\pi}\frac{\text{Amp}}{\text{meter}}$$

A complete set of equivalents for magnetization is

$$\boxed{\mathbf{1}\ \frac{\mathbf{EMU}}{\mathbf{cm^3}} = \mathbf{4\pi\ Oersted} = \mathbf{10^3}\ \frac{\mathbf{Amp}}{\mathbf{meter}}} \qquad (2.17)$$

Remember, magnetization is often referred to as ´moment´.

As before magnetization has three equal representaions.

$m/V = \text{EMU/cm}^3$

$$Qm/\text{Area} = \frac{\text{EMU/cm}}{\text{cm}^2} \quad \text{and} \qquad (2.18)$$

$I/\lambda = \text{EMU/cm}^3$ = See problem 2.5

(2.18) is one of the forms that we will use later.

$\frac{NEWTON}{A\text{-}M} = \frac{W}{M^2}$ $WEB = \frac{NEWTON\text{-}M}{A}$

$1\ MAX = 1\ GIL\text{-}CM = \frac{10}{4\pi}\ A\text{-}CM$

$1\ GIL = \frac{10}{4\pi}\ AMP = \frac{10^{1}}{4\pi}\ A\text{-}M$

$1\ WEB = 1\ AMP\text{-}HENRY = \frac{10^7}{4\pi}\ A\text{-}M$

2.7 SUMMARY

$F \Rightarrow NEWTON = \frac{W\text{-}A}{M} = 10^5\ DYNE$

QUANTITY	COMMON SYMBOL	MKS	CGS-EMU	CONVERSION
MAGNETIC CHARGE	Qm	1 Amp-meter 1 Weber (1 A-M = μ_oWeb) $1\ A\text{-}M = 4\pi \cdot 10^{-7}\ WEB$ $1\ WEB = \frac{1\ A\text{-}M}{4\pi \cdot 10^{-7}}$	1 EMU/cm 1 Maxwell (1 EMU/cm = 4π Max)	= 1/10 A-m = $4\pi 10^{-8}$Web = 1/(4π•10) A-m = 10^{-8}Web
FLUX DENSITY MAG FIELD INTENSITY	B $1\ WEB/M^2$	1 Weber/meter² $= \frac{N}{A\text{-}M}$ 1 Tesla (1 Web/m² ≡ 1 Tesla)	1 Maxwell/cm² 1 Gauss (1 Max/cm² ≡ 1 Gauss)	= 10^{-4} Tesla $= 10^{-4}\ \frac{WEB}{M^2}$
PERMEABILITY of Space	μ_o	$\frac{4\pi}{10^7}\ \frac{Henry}{meter}$ or $\frac{Web}{A\text{-}M}$	$1\ \frac{Gauss}{Oersted}$	$= \frac{4\pi}{10^7}\ \frac{Weber}{Amp\text{-}meter}$
MAGNETIC FIELD MAGNETIZATION FORCE	H	1 Amp/meter	1 Oersted	= $10^3/4\pi$ Amp/meter
CURRENT	I	1 Ampere	1 Gilbert	= 10/4π Amp
MAGNETIC DIPOLE MOMENT	m	1 Amp-meter² 1 Web-meter	1 EMU 1 Max-cm	= 10^{-3}A-m² = $4\pi 10^{-10}$Web-m = $10^{-3}/4\pi$ A-m² = 10^{-10}Web-m
MAGNETIZATION	M	1 Amp/meter	1 EMU/cm³ 1 Oersted	= 10^3Amp/meter = $10^3/4\pi$ Amp/meter

$\frac{1\ EMU}{CM} = \frac{1\ M}{4\pi}$

1 JOULE = 1 NEWTON (ENERGY)

$4\pi\ Oe = 1\ EMU/CM^3 = 10^3\ A/M = 10\ A/CM$

Conversion examples.

$Oe = \frac{1}{4\pi}\ EMU/CM^3$

1. A coercivity of 1000 Oe is how many Ampere/meter? USE 4πM IN Oe

   From the row for H we see 1 Oersted = $10^3/4\pi$ Amp/meter. Multiply both sides by 1000 and we get

   1000 Oe = $10^6/4\pi$ Amp/meter =

2. A magnetic charge of 15 Ampere-meter is how many EMU/cm?

   From the row for Qm we see 1 EMU/cm = .1 A-m. This changes to 1 A-m = 10 EMU/cm. Now multiply both sides by 15 and

   15 A-m = 150 EMU/cm

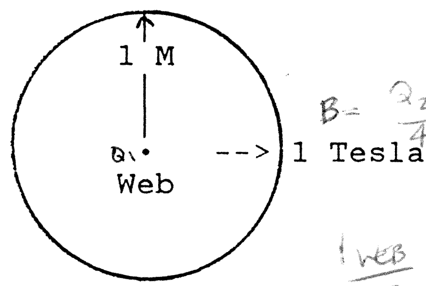
Problem 2.1

Starting with equations (2.1) and (2.2) work through the substitutions leading to equation (2.3)

Problem 2.2

Find the magnitude of the magnetic charge in the indicated units that has to be placed in the center of each of the spheres below to gives the indicated flux densities at the surface of the sphere.

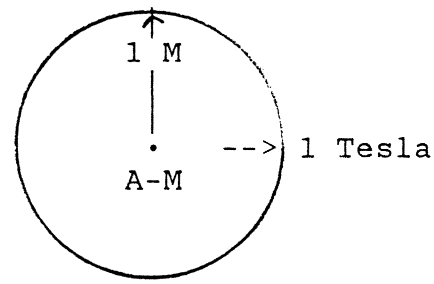
a.



$B = \frac{Q_2}{4\pi}$

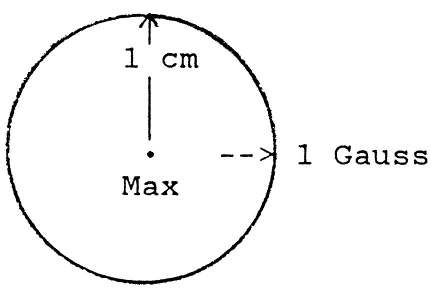
$\frac{1 \text{ WEB}}{M^2} = 1 \text{ TESLA}$

b.

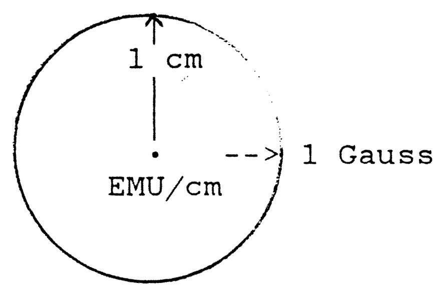


EQU 2.1
2.2
2.4

c.



d.



$1 \text{ AM} = \mu_0 \text{ WEB} = \frac{4\pi}{10^7} \text{ WEB}$

Problem 2.3

A bar shaped piece of magnetic material has a length l, width W and thickness t. It has a magntization Mr.

a. Show that the magnetic charge per unit width is Mr•t and is thus independent of l and W.

$Mr \cdot t = \frac{Gm}{A \cdot t} \cdot t = \frac{Gm}{A}$

b. What are the units of Mr•t in MKS?

c. What are the units in CGS-EMU?

d. What is the significance of the product of Mr•t•W?

Problem 2.4

Assume the material of problem 2.3 is a section of a magnetic coating Mr = 500,000 Amp/meter and t = 15 μinches. Find Mr•t in EMU units.

$1 EMU/cm^3 = 10^3 A/m$

Problem 2.5

For deriving equations (2.10) and (2.11) why aren't the charges of (2.3) rather than (2.4) and (2.5) multplied by length.

EQUIVALENCE RELATION — CONVERSION RELATION

$1 FT = \frac{12 IN}{12 IN/ft} = 1 ft \quad 1 FT = 12 IN$

Problem 2.6

The MKS units for magnetic moment, refect the equivalence of I•Area AND $Q_m \cdot l$ ~~equivalence of I•Area~~ and Qm•l. Find the equivalent form in CGS with the proper values. I. e. find the values of K and K_1 .

$$1 \text{ EMU} = K \text{ Gilbert-cm}^2 = K_1 \text{ Amp-cm}^2 = 4\pi \text{ Max-cm}$$

Problem 2.7

Equation 1.19 states the relationship between **B**, **H** and **M** as

$$B = \mu_o (H + M)$$

This is in MKS units. State the relationship in the shortest form in CGS-EMU units.

Problem 2.8

a. Convert the MKS results of problem 1.5 to the corresponding CGS values and units.

b. Rework problem 1.5 by first converting the given dipole moment to the proper CGS units and finding M, H & B in CGS units.

3. FERROMAGNETIC BEHAVIOR

Equations (1.11) and (1.18) imply rather simple relationships;

OUTSIDE MEDIA $\qquad\qquad$ WITHIN MEDIA

$$H = B/\mu \qquad\qquad H = B/\mu_o - M$$

however in ferromagnetic materials μ (or μ_r) is not constant but is a function of both the applied field and the previous magnetic history.

In a ferrormagnetic material the magnetic effects are produced by the motion of the electrons of the individual atoms.

Each atom acts like a tiny bar magnet.

In a material such a iron these atomic magnets over a region called a domain tend to orient themselves parallel to each other.

These domains tend to vary in size and shape from microscopic to a millimeter or so.

Each domain is like a little bar magnet but in unmagnetized iron the alignment of each domain is in either direction along any one of the three mutually perpendicular crystal axis and there is no net magnetization.

3.1 INITIAL MAGNETIZATION AND SATURATION Ms

If an unmagnetized sample is placed in an external field, **H**, that is parallel to one of the axes, some of the domains will with align with the field.

If this external field stars at 0 value and increases, the net induced magnetization, **M**, is as shown in Figure 3.1.

Some domains align easily and a few with great difficulty.

Magnetic saturation **Ms** is reached when all of the domains THAT WILL ALIGN are aligned.

The curve of Figure 3.1 is called the initial magnetization curve.

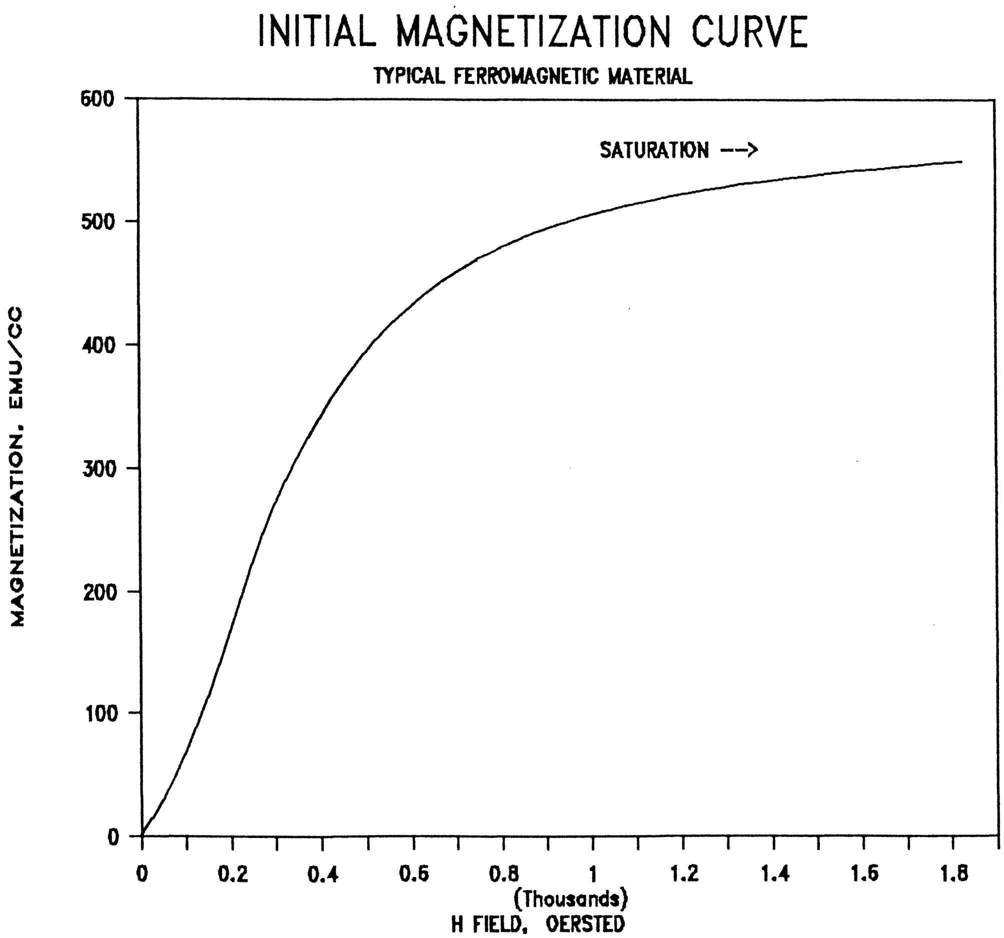


Figure 3.1

3.2 M-H LOOPS AND MAGNETIC REMANENCE Mr

When **H** is now reduced to 0, there is some decrease in **M** but most of the domains remain aligned and there is a remanent or permanent magnetization **Mr**.

As **H** is increased in the opposite, or negative, direction, **M** will decrease more rapidly and eventually reach 0.

This value of **H** is defined as the coercive force or coercivity **Hc**.

If **H** is increased to a large negative value and then back to a large positive value, **M** will behave as shown in Figure 3.2.

If the magnetic properties are the same for each orientation of the material it is isotropic. 90°, ETC

If there are differences in magnetic properties for different orientations, as is generally the case, it is anisotropic.

The ratio of the same parameter for, say, two orientations is called the anisotropy of that parameter. For example, "the circumferential to tangential remanent anisotropy of the coating is .2".

MAGNETIC HYSTERESIS LOOP (HARD MAGNETIC MATERIAL)

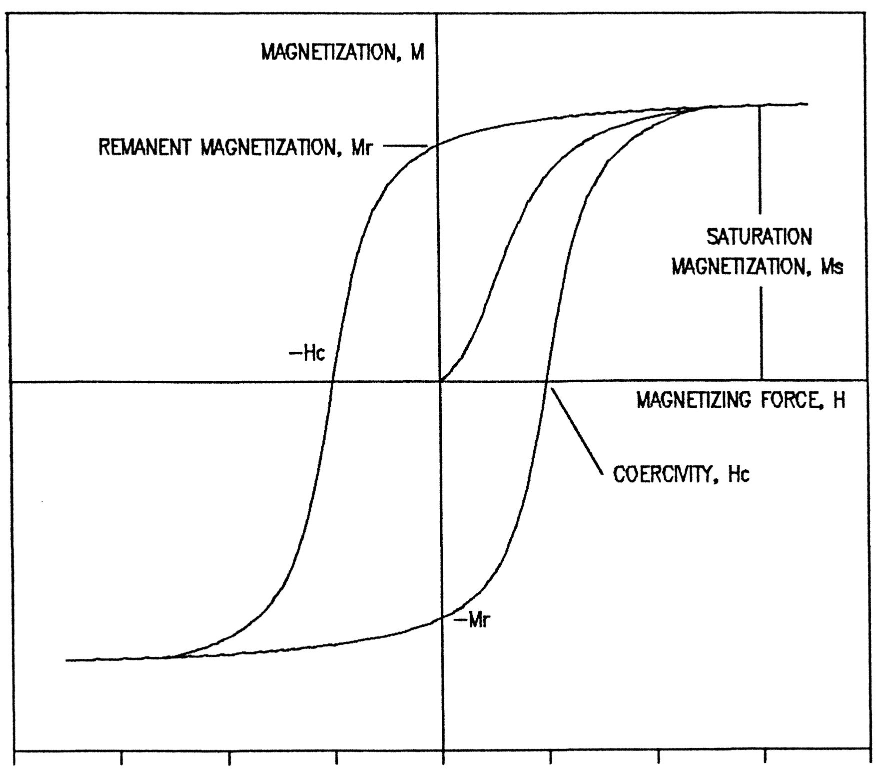


Figure 3.2

If **H** is increased and decreased in the positive and negative directions to values other than large all sorts of minor loops can be traced. Some examples are shown in Figure 3.3

MINOR HYSTERESIS LOOPS

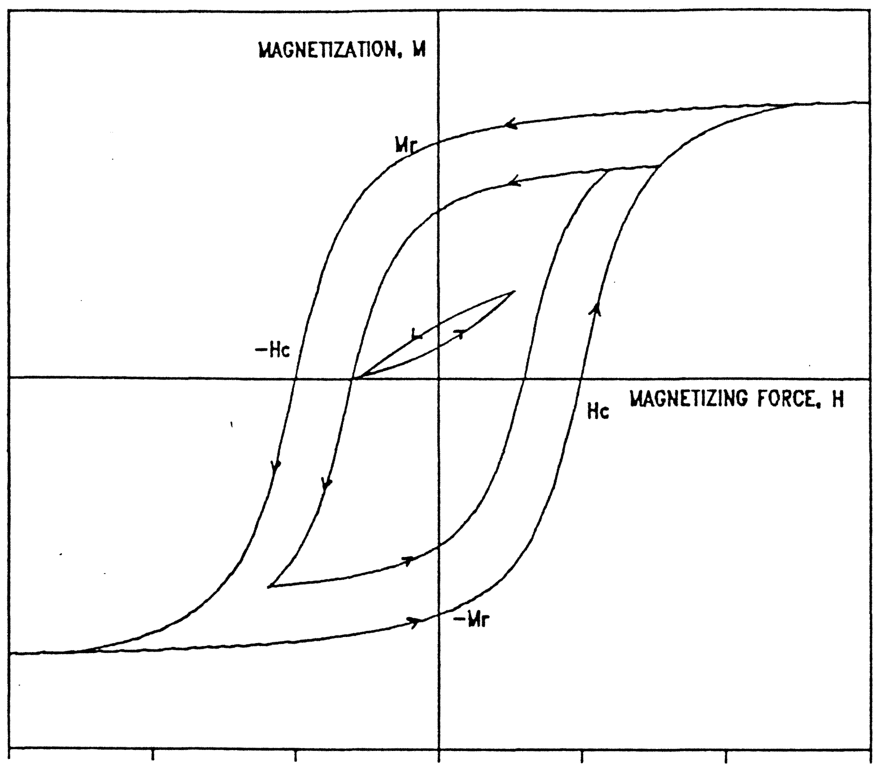


Figure 3.3

DC ERASE AT Mr or -Mr

AC ERASE AT 0

3.3 HARD AND SOFT MAGNETIC MATERIALS

Ferromagnetic materials with relatively large values of **Mr** and **Hc** are hard magnetic materials and those with relatively small values are soft magnetic materials.

Figure 3.2 is a hard magnetic material and Figure 3.4 is a soft magnetic material.

Hard magnetic materials are desirable for permanent magnets and recording materials.

Soft magnetic materials are desirable for electromagnets and recording heads.

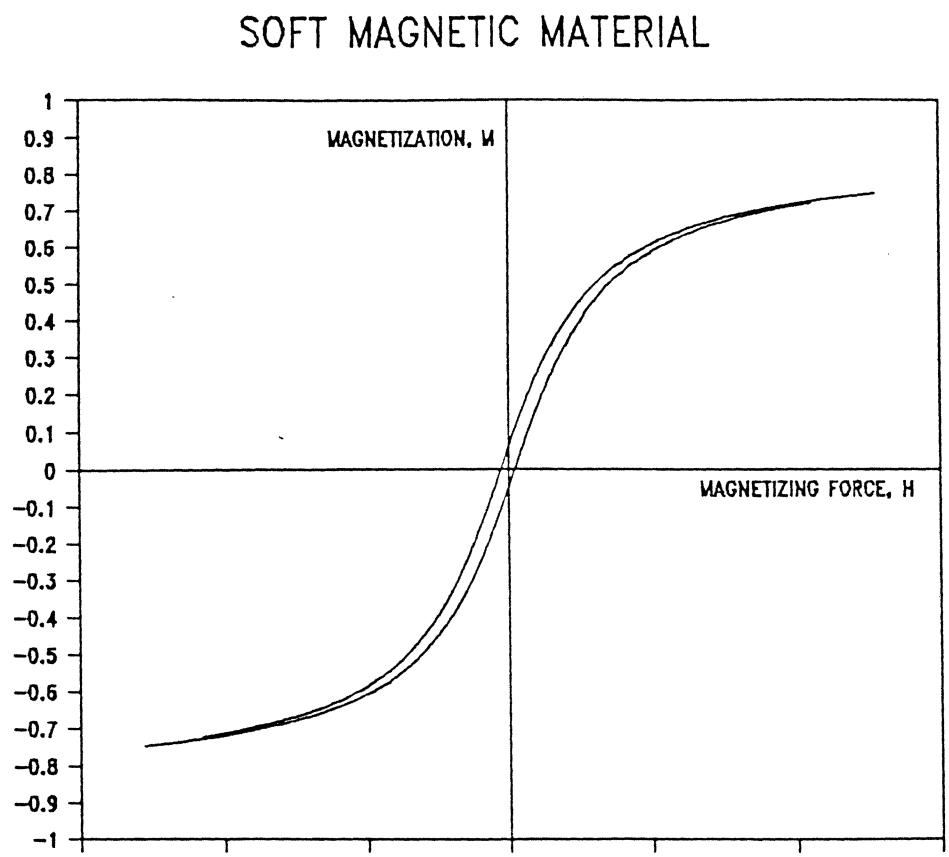


Figure 3.4

3.4 MAGNETIC AND COERCIVE SQUARENESS

Quantities that help to characterize the M-H loop and the material in addition to Mr and Hc are the magnetization squareness S and the coercive squareness S* (usually called S star).

These two quantities are shown in Figure 3.5.

$$S = Mr/Ms$$

$$S^* = H1/Hc = 1 - Mr/Hc \cdot \mathrm{CoTan}\beta$$

Where β is the angle between the H axis and the M-H line through Hc as shown in Figure 3.5.

In a magnet or recording material a high S (close to 1) is desirable in order to have as high a magnetic strength or read-back signal as possible.

A material with a high S* will require less H field to bring the magnetization to saturation and thus the remanent magnetization to Mr.

In the case of a recording material high S* material will have sharper transitions. A good recording material has an S* ≥.75.

SQUARENESSES S AND S*

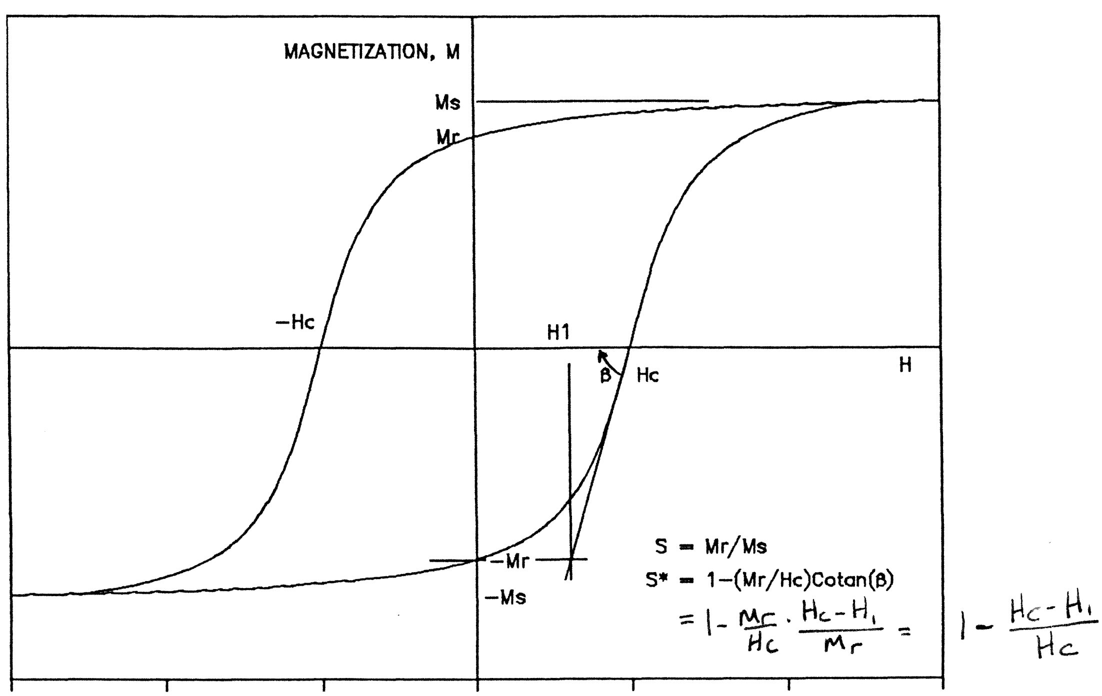


Figure 3.5

3.5 EFFECT OF A MEDIA SUBSTRATE

The curves of Figures 3.1 - 3.5 are as would be measured with pure samples of ferromagnetic magnetic materials.

When a small sample cut form a disk is measured, the substraight, even thought non-ferromagnetic, may be paramagnetic.

In paramagnetic materials there is a week induced magnetization in the same direction as the magnetizing force, **H**. When **H** is removed there is no remanent.

The effect on the M-H loop of such a substraight is shown in Figure 3.6. The magnetization in the substrate adds linearly to that of the ferromagnetic media.

Note the effect on the determination of Ms and S* and Hc.

M–H LOOP WITH SUBSTRATE EFFECT

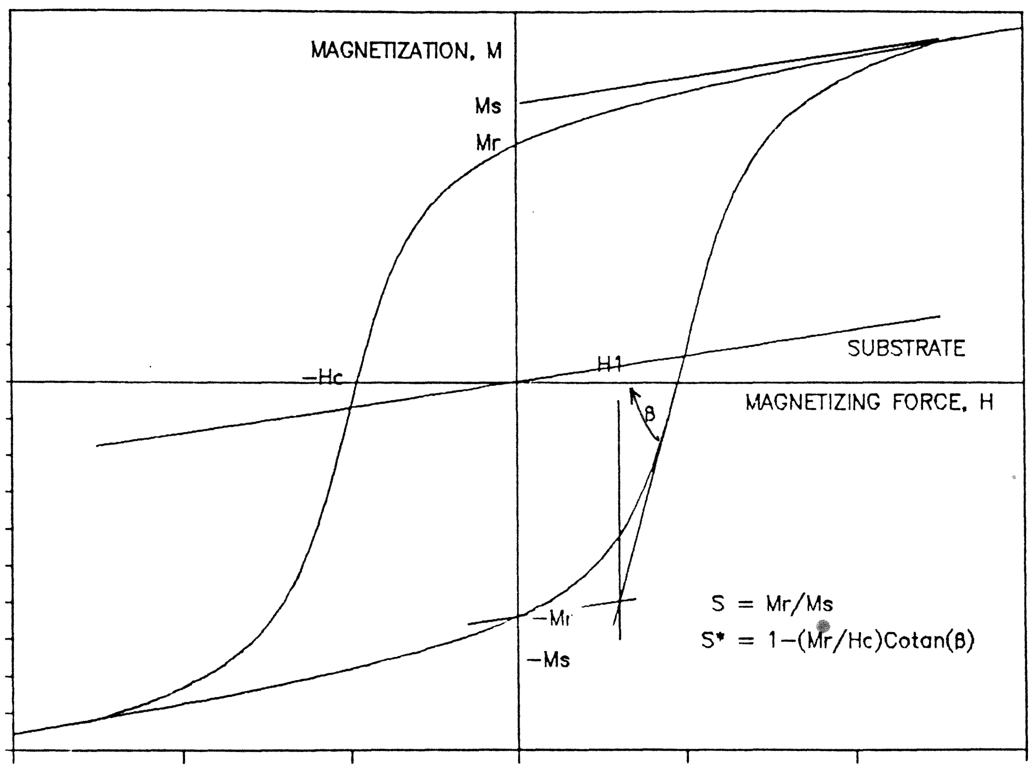


Figure 3.6

3.6 THE REMENANCE TRANSFER CURVE

If a hard ferromagnetic material is driven to satuation, say in the + H direction, and then H is brought to a value between 0 and -Hc, say some $-H_1$, and then to 0, the resulting remenance will be greater than the value of M corresponding to $-H_1$.

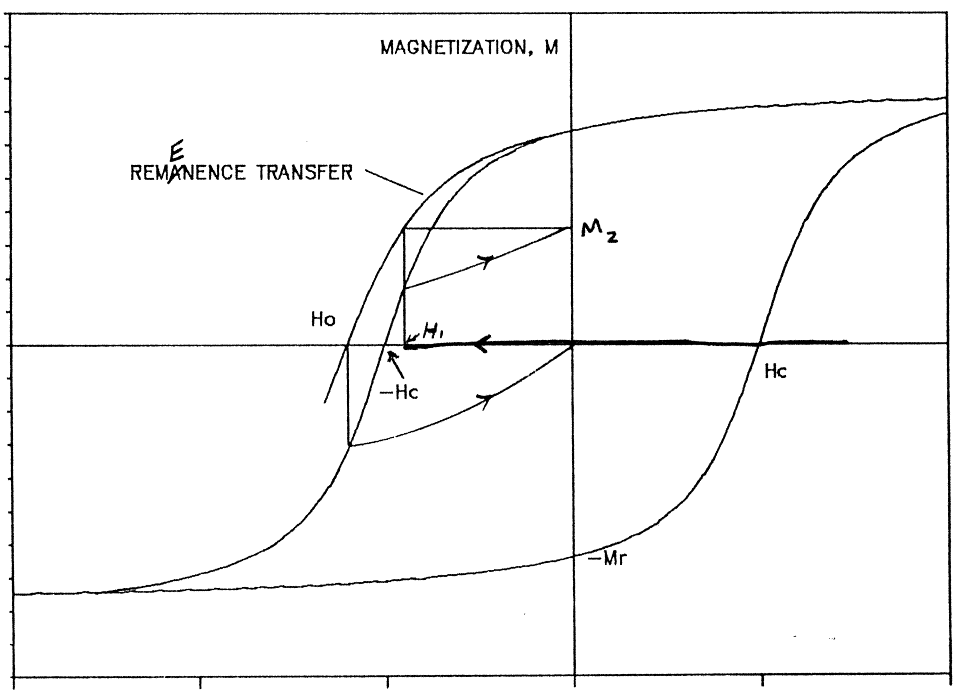
If this value of M is plotted for the value $-H_1$, and the process repeated for a contumueum of $-H_1$ values a new curve is generated as shown in Figure 3.6.

This curve is called the remenance transfer curve. It will be of use when we study the writing process.

Note that for the material to be left with M = 0 from the + saturated state H must be driven to -Ho. Correspondingly there is a +Ho.

Figure 3.6 is for illustration and is not necesserily accurate interms of the increasing separation of the remenance transfer and loop curves.

REMEMANCE TRANSFER CURVE



Remanence transfer
Remenat ... H as
a function of H

Figure 3.6

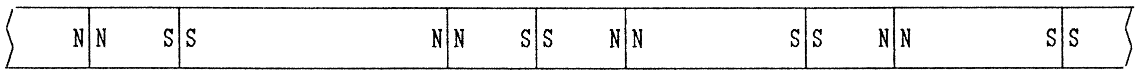
3.5 PROBLEMS

1. From the following M-H loops determine Hc, Ms, Mr, S and S*.

4. THE MAGNETIC TRANSITION

4.1 MAGNETIC RECORDING

The essence of magnetic recording is the creation and detection of a series of magnetic bars of alternating polarity and of varying lengths in a hard magnetic medium.



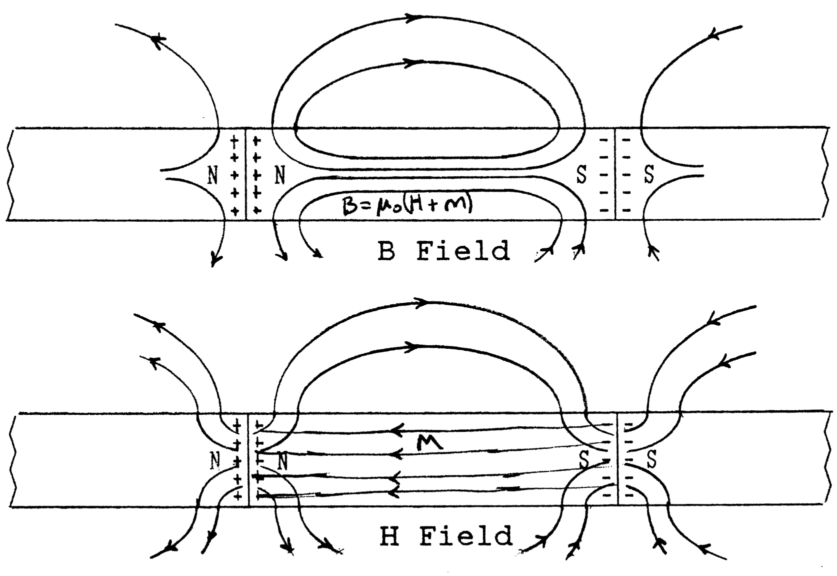
FLUX DENSITY

The B field is much like that shown on page 1.7 except that the flux does not exit from the ends but from the sides near the end and none of it crosses the transition plane. $B_x = 0$ right at the transition.

Also the magnetic charge at the transition is twice as large.

The external B field is concentrated at the transitions.

H = MAGNETIC FIELD
M = MAGNETIZATION



OUTSIDE MEDIA
H & B ARE THE SAME
M = 0
INSIDE MEDIA
H ORIGINATES & TERMINAT
AT TRANSITION
H << M

The trend is to higher and higher linear densities.

The magnetic limit to linear density is two fold:

1. how close the transitions can be packed in the medium and
2. obtaining adequate signal from reading heads small enough to resolve close transitions.

In this section we will examine the nature of a transition and some limits to closeness.

4.2 THE MAGNETIC TRANSITION

The following considerations apply in general to a transition in the medium or to the boundary between a magnetic medium and air. The primary difference are the values of **B** and **H** right at the boundary. At a boundary to a nonmagnetic medium they have finite values while at a transition they are both zero.

Mathematically there are three relationships that lead to these results:

Gauss´s law,

B = μ_o (M + H) equation (1.19) and

B being continuous.

Gauss´s law states that the net flux that comes out of a volume is equal to the charge within the volume. Stated more formally.

CHARGE

$$\int_S M \cdot ds = \int_V (Rho) \cdot dV = Qm \qquad (4.1)$$

CHARGE DENSITY

Where Rho is the magnetic charge per unit volume or charge density.

If the charge density is uniform over a small volume delta V, (4.1) becomes

$$\int_S M \cdot ds = (Rho) \cdot dV$$

and

$$\frac{\int_S M \cdot ds}{\text{delta } V} = Rho \qquad (4.2)$$

$B = \mu_o (M + H)$

The limit as delta V-->0 is defined as the divergence. Thus

$DIV = \frac{dB}{dx}$ IN A SINGLE DIMENSION

$$\text{div } M = Rho \qquad (4.3)$$

$= \mu_o \left(\frac{dM}{dx} + \frac{dH}{dx} \right) = 0$

Where div is the divergence.

$\frac{dM}{dx} = - \frac{dH}{dx}$

$$\text{div} \cdot B = 0 \qquad \text{and} \qquad (4.4)$$

$$\text{div} \cdot H = -\text{div} \cdot M \qquad (4.5)$$

IN 3 DIMENSIONS

By a straight forward consideration of the flux flows in and out of a small volume del x by del y by del z it is shown that

PARTIAL DERIVITIVES

$$\text{div } M = \frac{dMx}{dx} + \frac{dMy}{dy} + \frac{dMz}{dz} \qquad \text{CHARGE DENSITIES} \quad \frac{dm}{dx} = \rho = \frac{-dH}{dx} \tag{4.6}$$

Where Mx is the x component of M etc.

Further consideration of these equations leads to the the following conclusions.

The rate of change of **H** = the negative rate of change of **M**.

A large change in **M** gives rise to a large value of **H** which in turn acts to demagnetize or decrease the value of **M**.

$$\text{div}\cdot H = -\text{div}\cdot M \tag{4.5}$$

There cannot be a discontinuity in **M** at the boundary of the media.

The rate of change of **M** also equals the magnetic charge density, Rho, i.e. Qm/unit volume.

$$\text{div } M = \text{Rho} \tag{4.3}$$

Thus the magnetic charge extends into the medium a short distance from the boundary or transition.

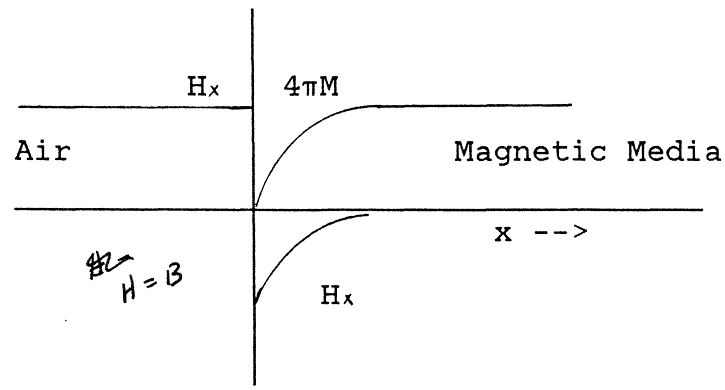
An equilibrium is reached such that **M** drops to 0 at the boundary or transition.

In the case of a boundary to air, **H** starts out with a value = **M** ($4\pi M$ for CGS) at the boundary and decreases to B/μ, or 0 for media of high μ.

In the case of a transition **H** has to be 0 right at the transition since both **B** and **M** are. **H** will increase rapidly to some maximum value and then decrease to B/μ.

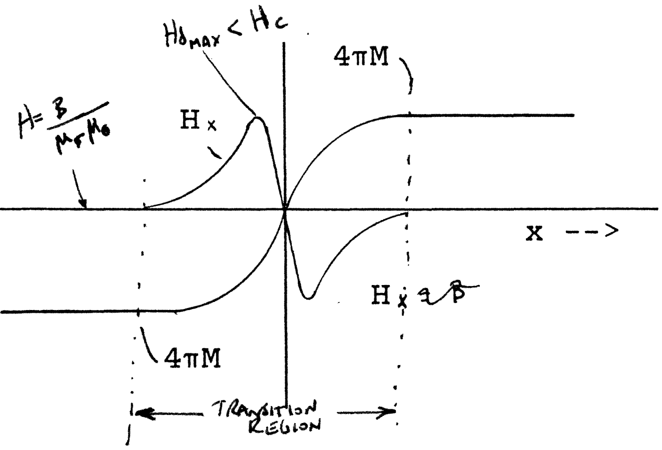
Thus, the transition has a finite length over which the values of **M**, **H** and Qm are all changing.

H and **M** as functions of x look like this.



x=0
BOUNDARY WITH AIR

MEDIA CANNOT SWITCH ITSELF



x=0
MEDIA TRANSITION
FLUX REVERSAL

SELF DEMAGNETIZATION
H_x DEMAGS M

The length of the transition depends on two things.

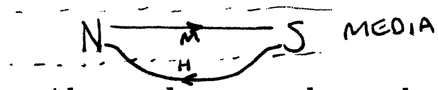
1. The demagnetizing field limit i.e. $\mathbf{H_D}$ can not exceed **Hc**

2. The sharpness of the magnetization field, **H**, from the writing head.

We will first examine the demagnetizing field limit.

4.3 THE DEMAGNETIZING FIELD AND TRANSITION LENGTH

H with in a magnetic media, arising from the magnetic charges that are generated by the magnetization **M**, is called the demagnetizing field because it acts to decrease the magnetization.

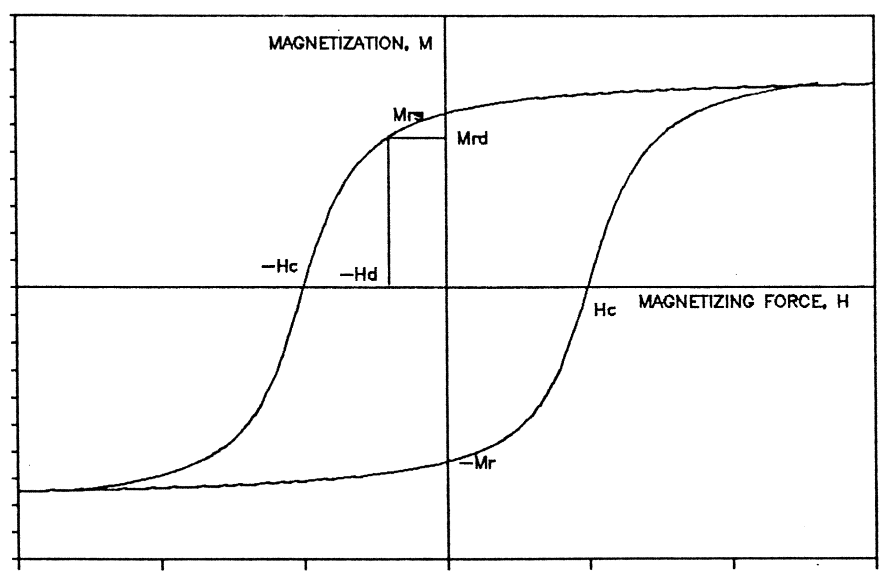


While **M** begins on negative or south poles and ends on the positive or north poles, **H** begins on the positive charge and ends on the negative. (OPPOSITE)

The field H_D drives **M** down the M-H loop in the second quadrant.

H_D grows from insignificance to a value not to exceed Hc as you approach the transition.

EFFECT OF DEMAGNETIZATION FIELD, Hd



H can be rigorously determined in the transition region by summing the contribution from each magnetic charge.

The charge in turn is the volume integral of the divergence of **M**. Thus **H** has the form

$$H_D \approx \int \frac{-\operatorname{div} M}{r^2}\, dV \tag{4.7}$$

But **M** is also dependent on H_D. A rigorous solution is iterative and nonlinear.

Such a solution is called self consistent.

It has to be carried out over a large number of mesh points and is not very practical.

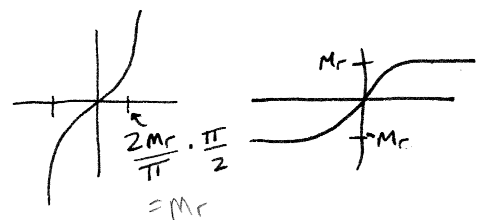
Self consistent results also require some initial assumption of the form of the final result.

If **M** is initially assumed to be a step function from **-Mr** to **Mr** at the transition, a final distribution of **M** is obtained.

If **M** is initially assumed to be a ramp function from **-Mr**to **Mr** a different final distribution is obtained. Etc.

One very useful form is the arctangent. This is the form that we will use for the transition in determining its effect on the read-back pulse.

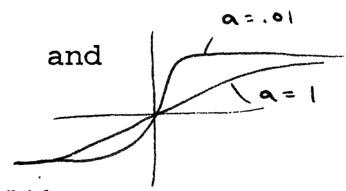
$$\boxed{M(x) = \frac{2Mr}{\pi} \operatorname{Tan}^{-1}\left(\frac{x}{a}\right)} \qquad (4.8)$$

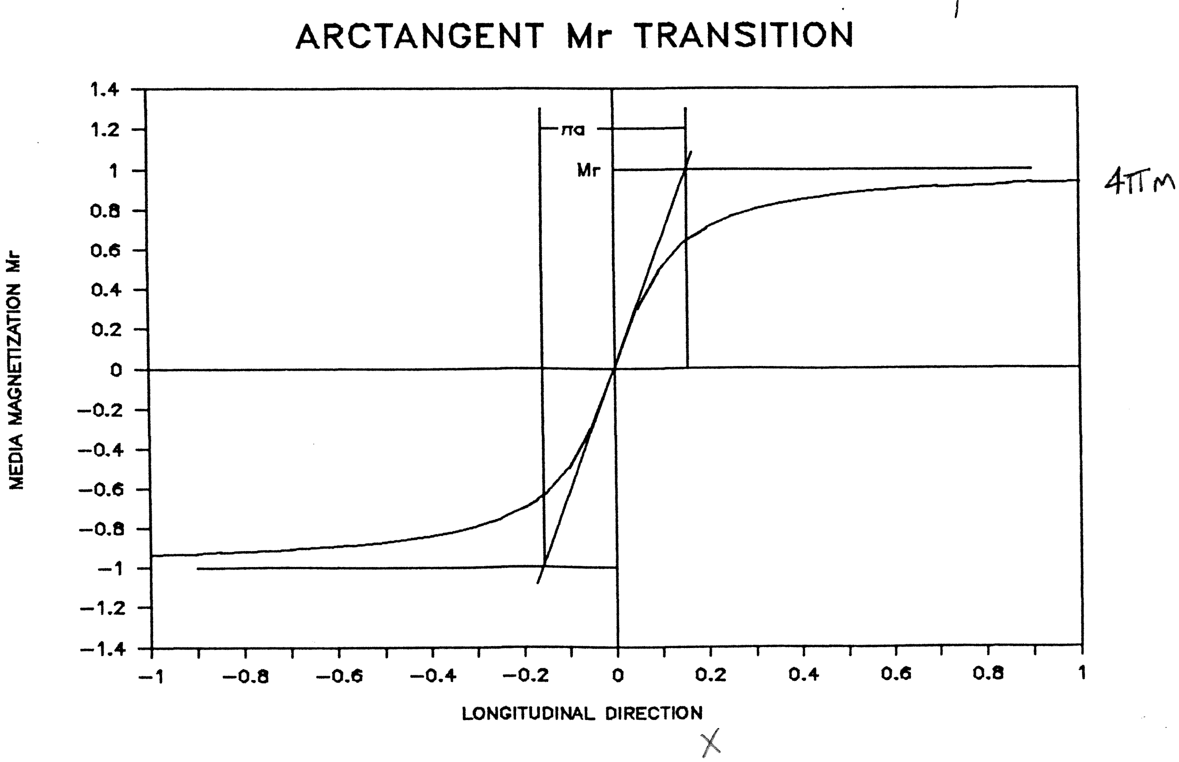


Where

a is called the transition parameter and

πa the transition length.





For the arctangent transition in CGS units.

t = THICKNESS OF MEDIA

$4 M_r \tan^{-1}(\infty) = 4 M_r\left(\frac{\pi}{2}+\frac{\pi}{2}\right) = 4\pi M_r$

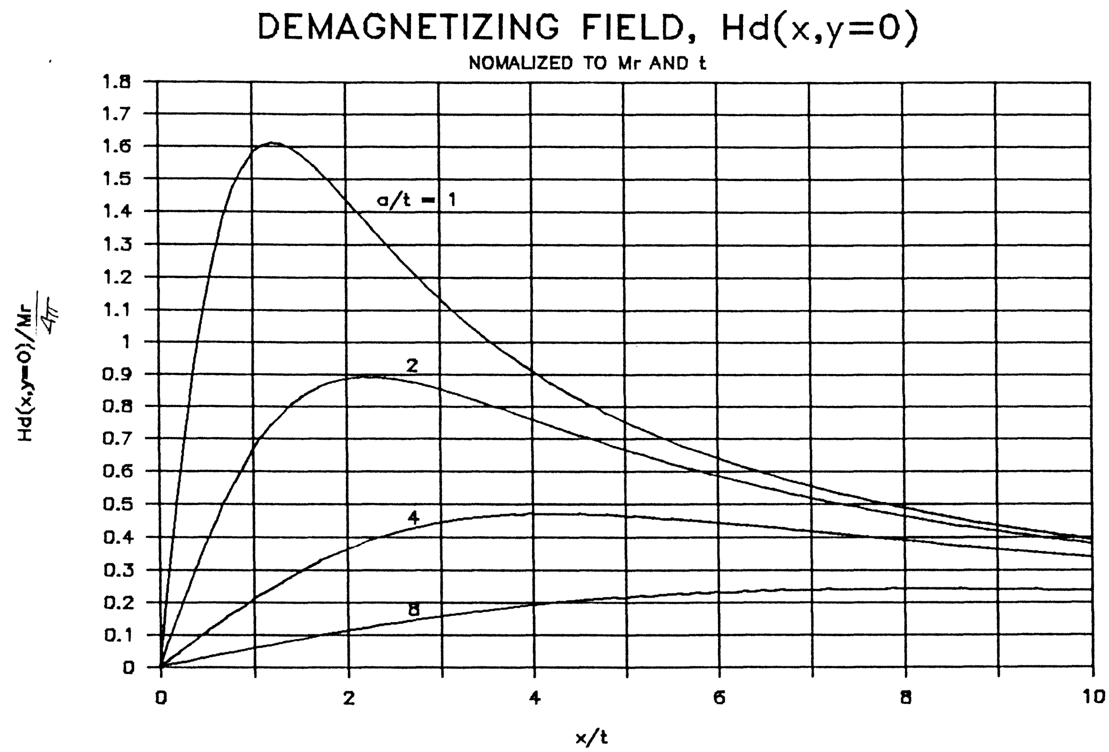
$$Hd_x(x,y) = 4Mr\cdot\left[\tan^{-1}\left[\frac{(t/2+y)\cdot x}{x^2+a^2+|t/2+y|\cdot a}\right] + \tan^{-1}\left[\frac{(t/2-y)\cdot x}{x^2+a^2+|t/2-y|\cdot a}\right]\right] \tag{4.9}$$

$4M_r\,[\;\Rightarrow \frac{\pi}{2} + \pi/2\;] \Rightarrow 4\pi M_r$

with $y = 0$ (the center of the media) and dividing numerator and denominator by t^2 (4.9) becomes

$$\frac{Hd_x(x,y=0)}{Mr} = 8\cdot\tan^{-1}\left[\frac{1/2\cdot(x/t)}{(x/t)^2 + (a/t)^2 + 1/2\cdot(a/t)}\right] \tag{4.10}$$

NORMALIZED OVER MEDIA THICKNESS



The effect of y unequal to 0 is not strong. For $y = t/2$ the values for Hx are 10 to 20% lower.

Demagnetization is of significance when writing at high linear densities.

It adds or subtracts from the writing field resulting in

1. requiring a larger writing field than at lower density

2. a shift in the location of the transition.

We will ~~looks~~ look at these efffects in detail later.

For an arctangent transition the maximum value of **Hx** is

$$Hd_x(max) = 8Mr \cdot \tan^{-1}\left(\frac{t}{4a(1 + t/2a)^{1/2}}\right) \quad (4.10)$$

Setting $Hd_x = Hc$, since Hx can not exceed Hc, we get for the transition parameter **a**

FOR APPROXIMATION TO BE ACCURATE

$$\boxed{\mathbf{a} \approx \frac{\mathbf{2Mrt}}{\mathbf{Hc}} \equiv \mathbf{a_o}} \qquad \frac{t}{4} << a_o \quad (4.12)$$

$$\frac{Hc}{8M_r} << 1$$

And for the transition length

$$\pi \cdot a_o = \frac{2\pi Mrt}{Hc}$$

$\mathbf{a_o}$ is often used as a key characteristic of ~~the~~ a media.

It is the minimum possible value of **a**. UNITS? METERS

In an actual written transition **a** will be increased by the effects of S* and the gradient of the write head field.

When we cover the writing process, we will modify **a** to include a broader range of effects.

$$\frac{2M_r t}{Hc} - \frac{t}{4}$$

4.4 PROBLEMS

Problem 4.1

Find **a** from equation (4.10) for $Hd_x(max) = Hc$ without making any approximations. What are the approximations that lead to (4.11)? Problems 2 and 3 with let you examine the validity of these approximations

WITH $y=0$

$2.35\ Hd = Hc$

Problem 4.2

A particulate disk has an Hc of 500 Oe, Mr of 75 EMU/cc and a t of .25 microns.

a. Find a_0 and πa_0.
b. Find $Hd_x(max)$
c. Check the validity of the approximations of problem 1.
d. Find a_0 and Hx(max) using the exact equation for a_0.

Problem 4.3

A thin film disk has an Hc of 500 Oe, Mr of 500 EMU/cc and t of 300 Å.

a. Find a_0 and πa_0.
b. Find $Hd_x(max)$
c. Check the validity of the approximations of problem 1.
d. Find a_0 and $Hd_x(max)$ using the exact equation for a_0.

Problem 4.4

What recording differences would you expect to see between the disks of Problems 2 & 3?

Problem 4.5

Equation 4.9 is stated to be in CGS units. Why isn´t the coeficient of the Atan factor $4\pi M$ instead of just 4M?

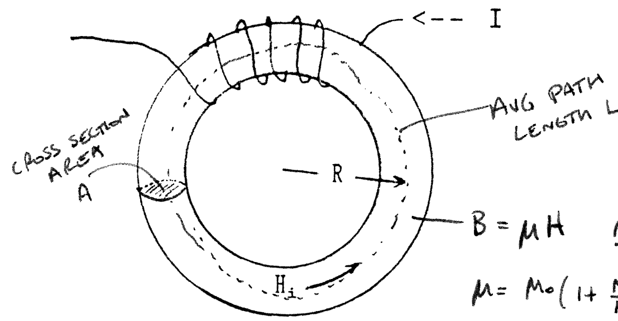
5. THE RECORDING HEAD FIELD

5.1 THE MAGNETIC CIRCUIT AND RELUCTANCE

Consider a magnetically soft iron toroid of mean radius R, a uniform cross sectional area A_i and with N turns of an insulated conductor carrying a current I.

From Ampere´s law, equation 1.7

$$NI = \int \frac{B_i}{\mu_i} \cdot dl = \frac{B_i}{\mu_i} \cdot L$$



Multiplying by A_i / A_i

$$NI = BA \cdot \frac{L}{\mu A} = \Sigma Flux \cdot Rel$$

$B = \mu H$ MKS

$\mu = \mu_o \left(1 + \frac{M}{H}\right)$

$= \mu_o \mu_r$

Where

BA = ΣFlux, the total flux

$L = 2\pi R$

$L/\mu A$ = Rel, the Reluctance

$B = H + 4\pi M$ EMU

$= H\left(1 + \frac{4\pi M}{H}\right) = \mu_r H$

$(\mu_o = 1)$

There is an analogy between this "magnetic circuit" and an electrical circuit where

E α NI = Potential or Magnetomotive Force

I α Flux Both are continuous

R α Reluctance, Both are proportional to L/A

If the flux path is made of sections of different geometries and materials, the flux due to NI is inversely proportional to a serial summation of the reluctances around the flux path.

$$\Sigma Flux = \frac{NI}{Rel_1 + Rel_2 \; .. + Rel_n} = \frac{NI}{\Sigma Rel} \qquad (5.1)$$

In any given section of the path (say the nth section)

$$H_n = B_n / \mu_n = \frac{\Sigma Flux}{A_n \mu_n} \cdot \frac{L_n}{L_n} = \frac{\Sigma Flux \cdot Rel_n}{L_n}$$

$$H_n = \frac{NI}{L_n} \cdot \frac{Rel_n}{\Sigma Rel} \qquad (5.2)$$

If there are abrupt changes in area or sharp corners, there may be flux leakage around some sections.

5.2 THE MAGNETIC CIRCUIT WITH AN AIR GAP

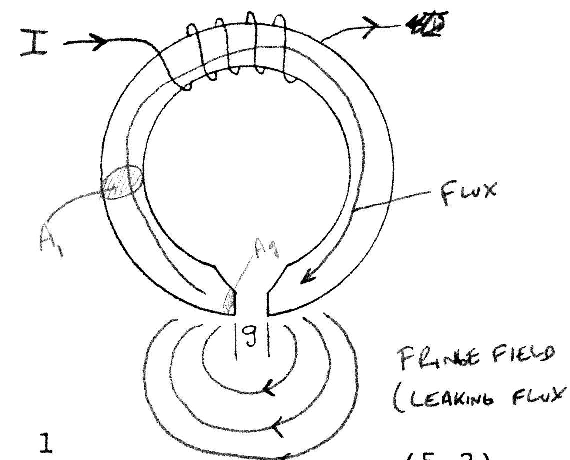
A magnetic recording head is essentially a magnetic circuit with an air gap in it.

It is the fringe field in the area of the gap that provides the magnetization force to magnetize the magnetic media.

Consider again the toroid. Let's cut a small gap of length g in it.

Also, for generality, let the area right in the region of the gap be different, say A_g.

The **H** field in the gap can be found from equation (5.2).



$$H_g = \frac{NI}{g}\cdot\frac{1}{(1 + Rel_1/Rel_g)} = \frac{NI}{g}\cdot\frac{1}{(1 + 1/\mu_r \cdot L/g \cdot A_g/A_1)} \qquad (5.3)$$

In the case of a recording head it is desirable to have H_g as large as possible. (5.3) can be written as

$$H_g = \frac{NI}{g}\cdot\varepsilon \qquad (5.4)$$

Where ε is called the efficiency.

$$\varepsilon = \frac{1}{\left(1 + \dfrac{LA_g}{\mu_r\, gA_i}\right)} \qquad (5.5)$$

Good efficiency requires $Rel_g \gg Rel_1$

Generally for a recording head $A_i > A_g$ and $\mu_r \cdot g > L$. High μ material is goodness.

Efficiency for film heads is generally .8 or better.

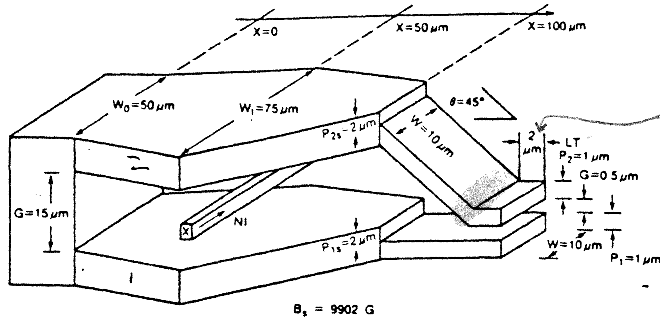
Efficiency is of more importance when reading than when writing since when writing I can be made as large as desired.

Equations (5.1) - (5.5) are only valid for a linear M-H relationship, i.e. constant μ, no hysteresis and no saturation.

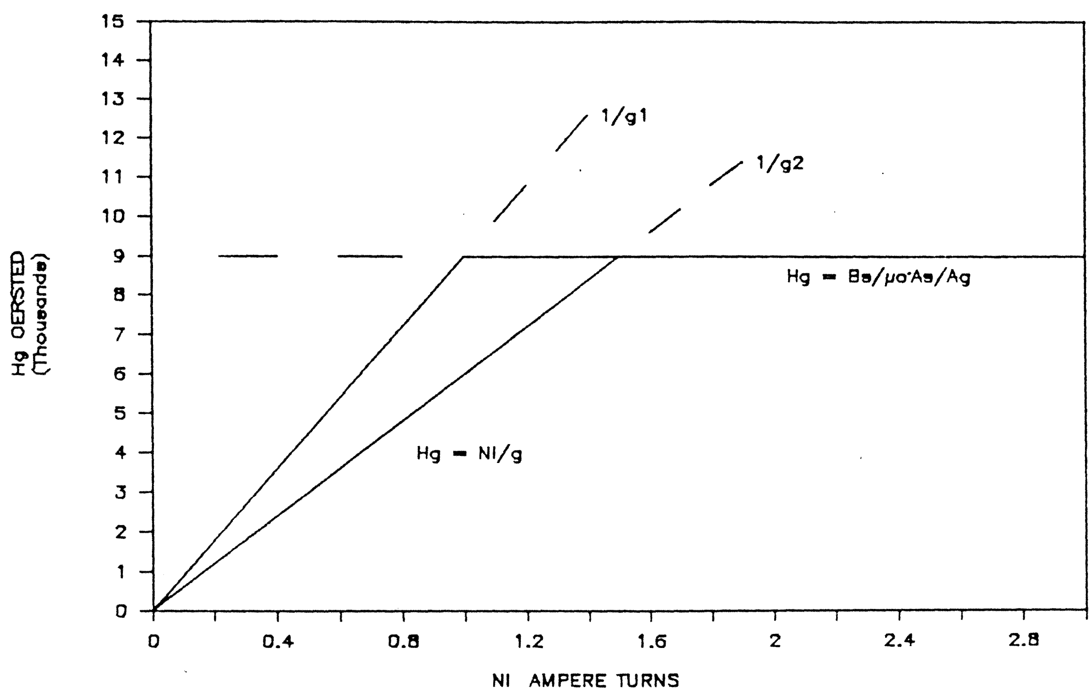
5.3 SATURATION WITHIN THE HEAD

I is generally increased until **M** and **B** in some area of the head reach saturation levels **Ms** and **Bs**. This will occur in the region of lowest cross sectional area.

For a thin film head this is normally in the sloped region of P_2.



GAP FIELD INVERSELY PROPORTIONAL TO THROAT HEIGHT



In the case of saturation the ΣFlux (5.1) becomes

$$\Sigma Flux = Bs \cdot As$$

FOR RING HEAD, A_g IS A_s

Also

$$H_g = \frac{Bs}{\mu_o} \cdot \frac{As}{A_g} \approx \frac{Bs}{\mu_o} \cdot \frac{P}{Th} \quad \text{For } Th > P \qquad H_g = \frac{Bs}{\mu_o} \qquad (5.6)$$

THROAT HEIGHT

Where As is the smallest or limiting cross sectional area and Th is the throat height (labled LT above).

Since P is set by design and Th is more uncrontrolled. H_g is inversely proportional to Th or the "throat height".

$$Hg = \frac{K}{h_g} = \frac{Bs}{\mu_o} \cdot \frac{P}{Th} \tag{5.7}$$

Throat height control from head to head is critical for consistant head to head writing capability .

The inductive head throat height is determined by a lapping process which can have a large tolerance due to the bow that occurs in each row when it is cut form the wafer.

If the poles are long such that A_g becomes the limiting area, H_g will be independent of Th.

$$H_g = Bs/\mu_o \tag{5.8}$$

Since $A_g = W_g \cdot h_g$ (gap width time gap height) H_g per unit width is inversely proportional to h_g or the "throat height".

$$\frac{Hg}{W} = \frac{K}{h_g} \tag{5.7}$$

Throat height control from head to head is critical for consistant head to head writing capability .

The inductive head throat height is determined by a lapping process which can have a large tolerance due to the bow that occurs in each row when it is cut form the wafer.

If the poles are long such that A_g becomes the limiting area, H_g will be independent of h_g .

$$H_g = Bs/\mu_o \tag{5.8}$$

5.3 THE RECORDING HEAD FRINGE FIELD

It is the fringe field at the air gap that enters the media and magnetizes the media in the write or record mode.

It is also the fringe field that shows the sensitivity of the the head to the media magnetization in the read mode.

At any point in space below the head the magnitude of **H** can be separated into x and y components. **Hx(x,y)** and **Hy(x,y)**.

For longitudinal recording **Hx** is of prime importance.

For a ring head (infinite pole tip lengths)

$$\boxed{Hx(x,y) = \frac{H_g}{\pi}\left[\tan^{-1}\left(\frac{x + g/2}{y}\right) - \tan^{-1}\left(\frac{x - g/2}{y}\right)\right]} \qquad (5.9)$$

This is known as the Karlquist expression.

Where

H_g is the gap field as in (5.4)

g is the gap length

x = 0 in the center line of the gap

y = 0 at the end of the gap

It is used extensively in the literature and in texts for the head field for a head with very long poles such as a ferrite head.

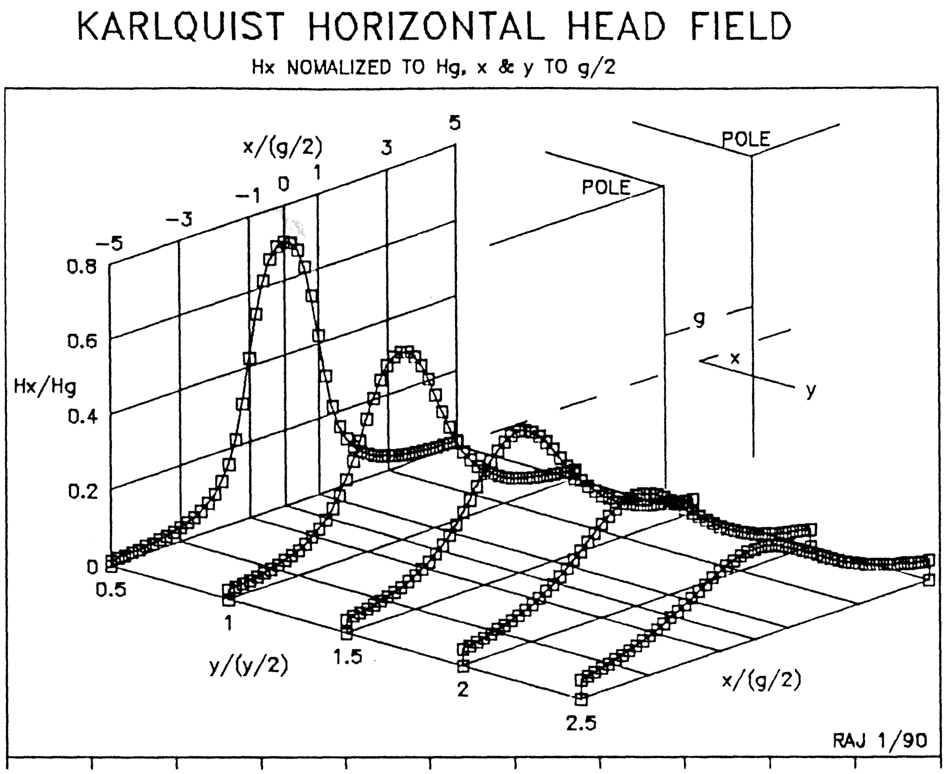
It is good for values of $y \geq g/2$.

The expression for a head with finite pole tips, such as a film head, includes the Karlquist expression plus expressions for each of the pole tips. We will look at this later.

The Karlquist expression for Hy(x,y) is

$$Hy(x,y) = \frac{H^{g}}{2\pi}\cdot \ln\left[\frac{(g/2 - x)^2 + y^2}{(g/2 + x)^2 + y^2}\right] \qquad (5.10)$$

Hx(x) for constant values of y is shown below. As y increases Hx(x) spreads out and loses amplitude.

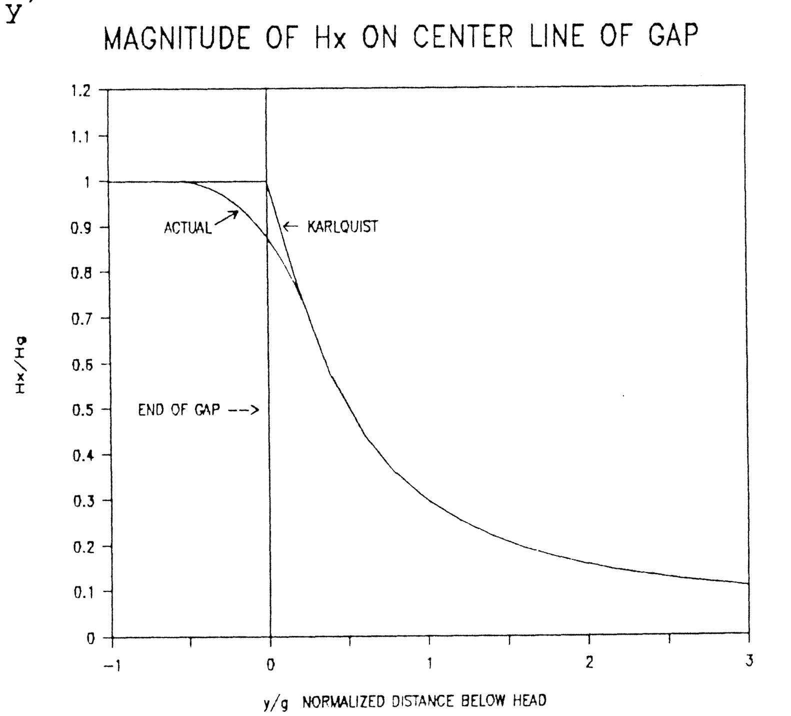


The magnitude of Hx along the y axis is found from (5.9) with x = 0.

$$Hx(x=0) = \frac{2H_g}{\pi} \cdot \tan^{-1}\left(\frac{g}{2y}\right) \tag{5.11}$$

By this equation the peak value increases, as y goes to 0, to the value of H_g right at the beginning of the gap and then has a constant value of H_g within the gap.

In reality there is a smooth transition with the value not reaching H_g until some distance within the gap.



The locus of points for which Hx is constant is found from equation (5.9) and letting Hx be a constant value.

$$x^2 + \left[y - \frac{g}{2}\cdot\mathrm{Cot}\left(\frac{\pi Hx}{H_g}\right)\right]^2 = \left[\frac{g}{2}\cdot\mathrm{Cot}\left(\frac{\pi Hx}{H_g}\right)\right]^2 + (g/2)^2 \qquad (5.12)$$

$(X+0)^2$

$$= \left(\frac{g}{2}\right)^2\left[1 + \mathrm{Cot}\left(\frac{\pi Hx}{Hg}\right)\right]^2$$

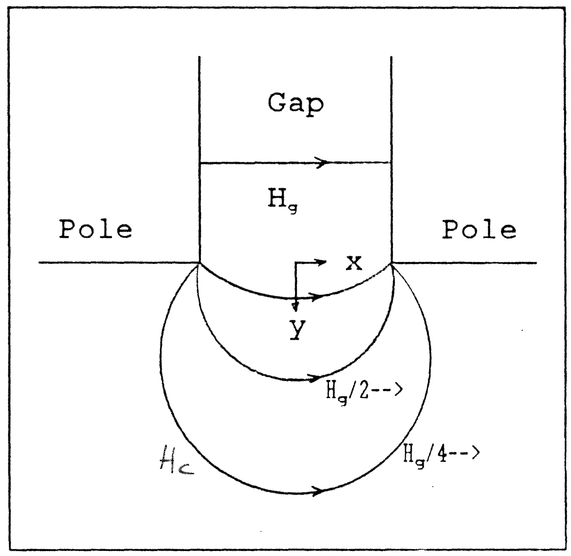
This is the equation of a circle

with center at

$$x = 0, \qquad y = \frac{g}{2}\cdot\mathrm{Cot}\left(\frac{\pi Hx}{Hg}\right)$$

and radius of

$$\frac{g}{2}\cdot\left(1 + \mathrm{Cot}^2\left(\frac{\pi Hx}{H_g}\right)\right)^{\frac{1}{2}}$$



Constant Field Contours

Contours of constant **H** are a family of circles with their centers on the bisector of the gap and all touching the conners of the gap.

The equation starts to break down as y becomes less than g/2. The result is that the contours do not all converge on the corners but will enter the poles slightly away from the conners. The gap corners will saturate.

All things considered, the Karlquist field expressions are pretty good even to values below y = g/2. The inaccuracies are deviations form the circular, constant Hx contours near the head and the smooth transition of the peak value to the magnitude of H_g.

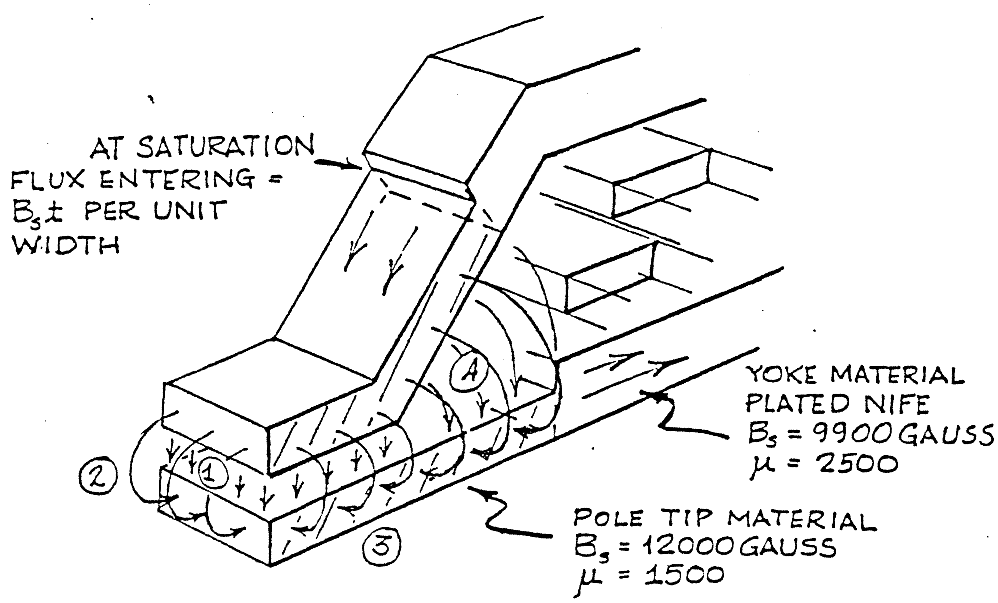
5.4 EFFICENCY LOSSES FOR NARROW TRACK HEADS

Equation (5.5, 6 and 7) assume that the head is much wider than throat height. Therefore all of the fringe field is in the y direction.

For very narrow heads this assumption is not true.

There is significant flux at the sides of the head as well as in the sloped region of the head.

Arnoldussen presents a detailed reluctance model including these losses.



PROBLEMS

Problem 5.1

A ring head is made from a material with μ_r = 1000 and $4\pi Ms$ = 10,000 Gauss. It has a gap of .5 microns and the gap has a rectangular area of 10 microns (width) by 2 micons (height or throat). The core of the head has a cross sectional area of 80 microns^2 and a length of 250 microns.

a. Find the head effeciency ε. (5.5)

b. What is the maximum field that can be obtained in the gap?

$Hg = 10{,}000 = 4\pi Ms$ Oe

c. If the head has 15 turns, what current is required to obtain the maximum field in the gap?

$Hg = 10{,}000 \cdot \frac{10^3}{4\pi}$ A/M $= 7.9 \cdot 10^5$ A/m $\quad I = \frac{Hg\, g}{N\epsilon} = .03$ A

d. Make a plot of the x component of the gap field for a distance up to 1 micron below the gap. Eq 5.11 pg 5.6

Problem 5.2

If the head of problem 1 is a thin film head, like shown on page 5.3 and the thickness of the sloped region is 1 μ,

a. What is the maximum Hg?

b. What can you say about the current required to just obtain the maximum Hg?

Problem 5.3

Sketch the Karlquist Hy(x,y) as a function of x for several values of y. (A figure similar to that for Hx(x,y) on page 5.4)

Problem 5.4

Prove the last statement of Page 5.4

Problem 5.5

Derive equation (5.12) from (5.9). (Only for the mathadextrous.)

6. THE WRITING PROCESS

6.1 OVERVIEW

The purpose of the writing process is to create a series of magnetic bars of alternating polarity in a hard magnetic medium of lengths varying in agreement with an input data stream.

The criteria for good magnetic writing is three fold.

1. To generate sharp well defined transitions between the magnetized regions,

2. To space the transitions proportionally with the write clock intervals and

3. To magnetize the media between the transitions to the maximum state, Mr, and there by erase the previously written state

Failure to adequately meet these criteria will adversely impact the the linear density capability of the system, the accurate reproduction of the input bit spacing and the readback signal to noise ratio (SNR).

Head/disk parameters that improve writeability will on the other hand also decrease SNR and density capability.

Thus how well each of these criteria is met is an intentional compromise. We will examine this compromise later.

In this section we will focus on the mechanics of the write process and how it affects the criteria for good writing.

There are several more or less independent effects that combine to determine ~~the~~ how well the 3 criteria are achieved. These effects are:

1. The base transition length of the media πa_o ,

2. The write head field gradient, and field strength,

3. The thickness of the media, primarily in the case of particulate media,

4. The distance moved during the switching time,

5. The current rise time of the head

6. The rise time of the flux to the input current. (μ is complex and has a reactive component at high data rates.)

7. The effect of demagnetization from the leading portion of the gap field on the trailing and writing portion of the gap field.

8. The effect of the direction of the previous magnetization in the region being written

9. The effect of demagnetization from the transitions just written.

10. The effect of the direction, relative location and sharpness of previously written transition.

11. The effect of image charges within the head above the media.

12. The write process is an iterative and interactive process.

These factors in turn relate back to the magnetic, geometric and electrical parameters of the head and disk.

There is, with only a few exceptions, no one for one relationships between the 3 levels of causes and effects.

These factors are of varying importance.

Some have linear effects while others have nonlinear effects.

To some extent each can be calculated but with varying degrees of approximations.

TRANSITION LENGTH FIELD STRENGTH 9.

Historically effects 1 and 2 have been dominant and lead to a useful analytical result that combines easily with the read process.

THICKNESS OF MEDIA

Number 3 can be handled by an approximation.

DISTANCE MOVED

Number 4 is of minor significance.

CURRENT RISE TIME

Number 5 is manageable to some extent with higher voltage and current requirements. Inductance considerations will limit the number of turns at higher data rates.

Number 6 is also manageable to some extent with higher voltage and current. The delay is due to eddy currents in the head material and may ultimately required laminated structures.

Numbers 7 - 11 will cause the transition to be shifted and can have major effects on overwrite and peak shift in the case of small gap heads and thin film media. Some degree of calculation is possible for each of these effects.

The effects of numbers 1 - 7 are constant for each transition.

Numbers 8 - 11 are random and must be considered from a statistical or worst case stand point.

Number 12 makes all closed calculations at the best approximations. There are what are called self-consistent models for more accurate calculations but these are slow and computer intensive.

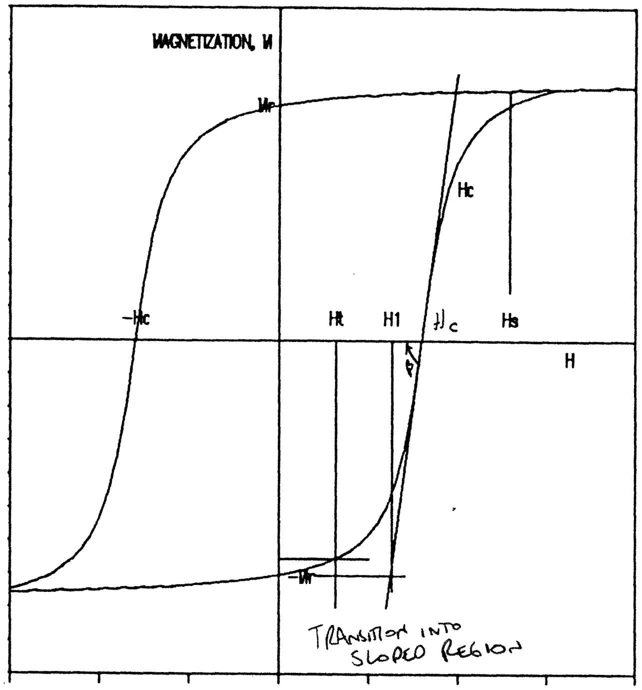
We will primarily focus our attention of numbers 1, 2 and 3. with some discussion of the others.

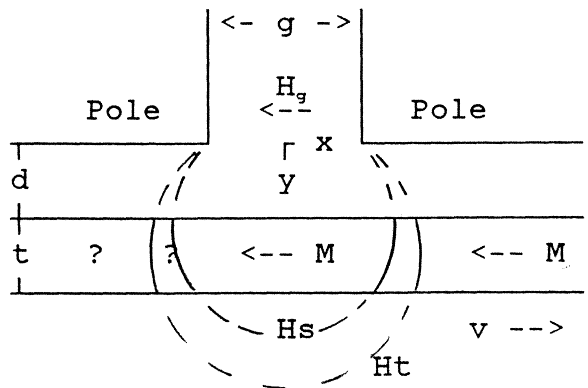
There are some good coverages of the several of the others in the references.

6.2 EFFECT OF WRITE HEAD FIELD ON THE TRANSITION

We will first look at the head/disk/transtion relationship pictorily and then analytically.

Consider a recoding media with this M-H loop.





For illustration purposes let us define additional values of **H**, the threshold field **Ht** and the saturation field **Hs**.

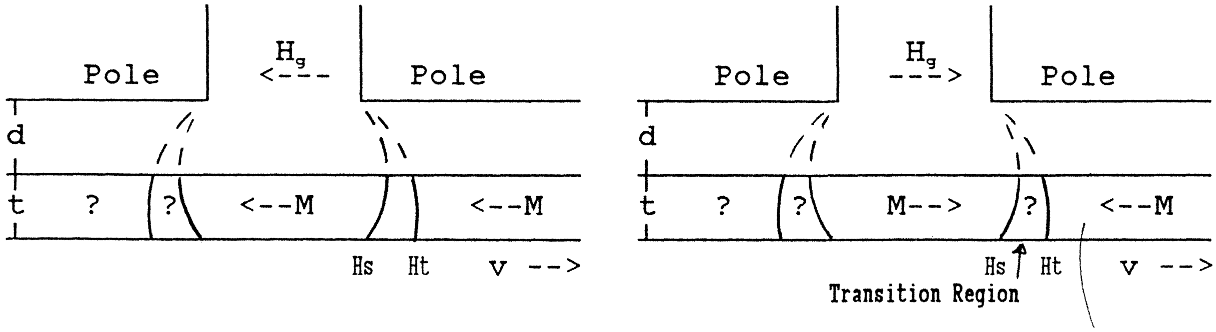
Let the media be placed a distance d from a recording head of gap g with a gap field of H_g in the -x direction and be moving to the right at a velocity v.

Circles of constant Hx = Ht and Hx = Hs are shown.

All of the media within the Hs circle will be switched in the Hx direction (-x) since within the circle Hx > Hs. MEDIA DRIVEN INTO SATURATION

Assuming that the field has been on for some time, we can conclude that all media to the right of the gap will be magnetized in the -x direction.

Let the field instantly switch to the +x direction.



Retains previous magnetization

The media in the Hs circle will be magnetized in the +x direction.

The media to the right of the Ht circle will remain magnetized in the -x direction and the media between the circles will be partially reversed depending on the proximity to the Hs and Ht circles.

This area will be a transition region.

This can be visualized from a plot of the Karlquist function Hx(x,y) and the M-H loop of the media as shown in Figure 6.1

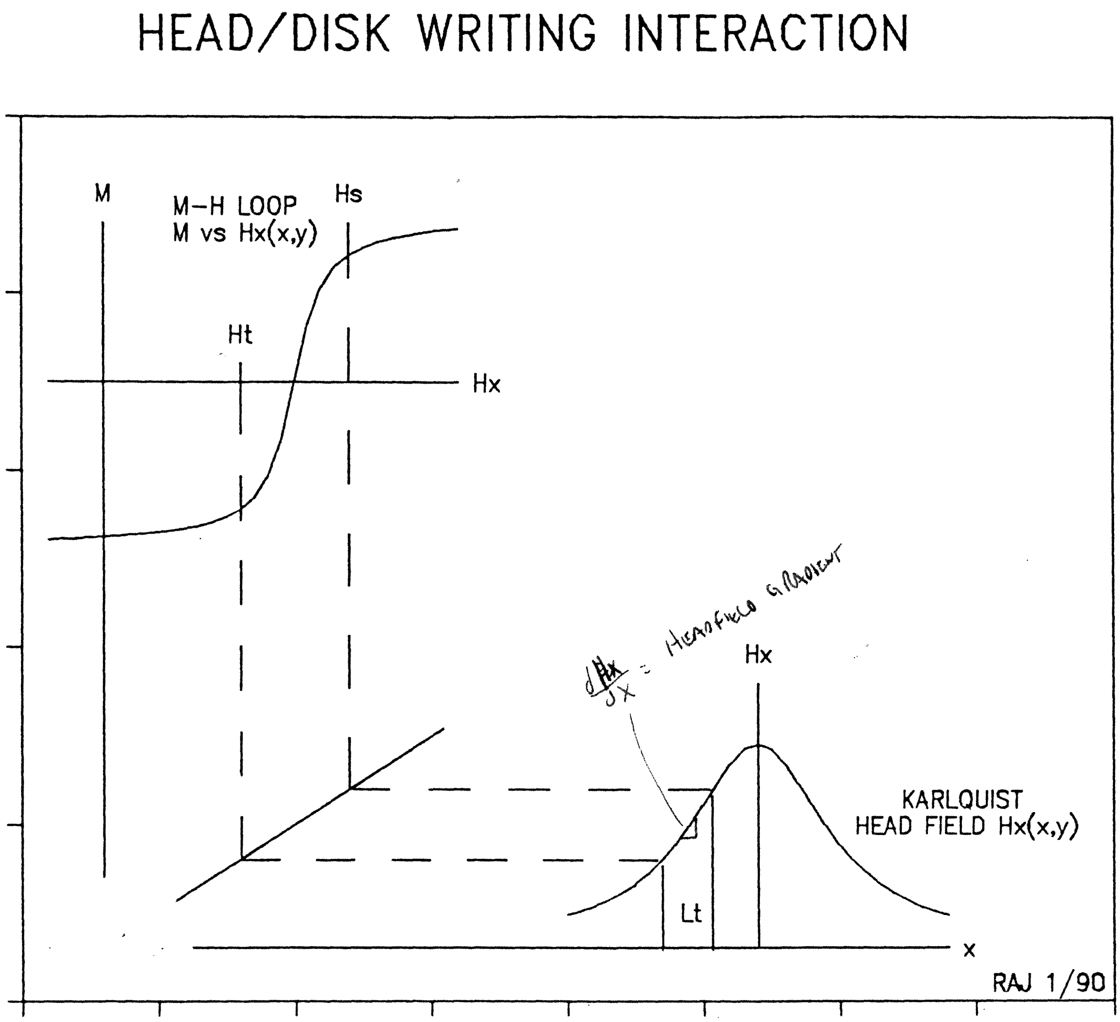


Figure 6.1

The steeper either the head field function (large dHx/dx or gradient) or the M-H curve (S* nearly = 1) is, the smaller the transition length will be.

The effect of the head field gradient is to cause the transition length to be greater than the minimum value of equation (4.11), 2•Mr•t/Hc.

We will discuss a numerical expression that combines both the head field gradient and the demagnetizing effects in the next section.

The transition can be plotted as Mx vs x as shown in Figure 6.2

TRANSITION PROJECTION

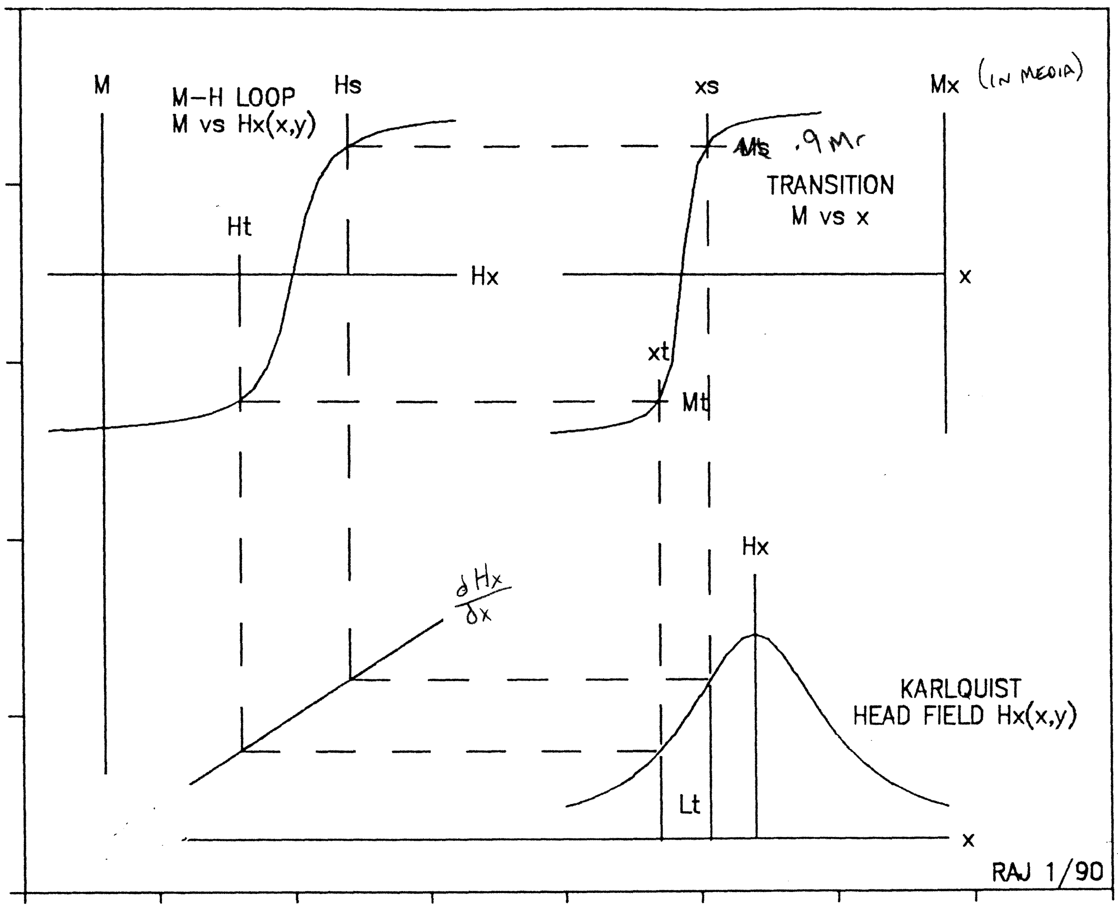


Figure 6.2

Since the Karlquist function is an arctangent function and the M-H curve is approximately and arctangent function, the transition will also be an arctangent function as we assumed before.

Analytically, we can first look at a simple expression that relates Hs - Ht to Hc and S* as shown below.

$$Ht = Hc - k \cdot (Hc - H1),$$

$$Hs = Hc + (Hc - Ht)$$

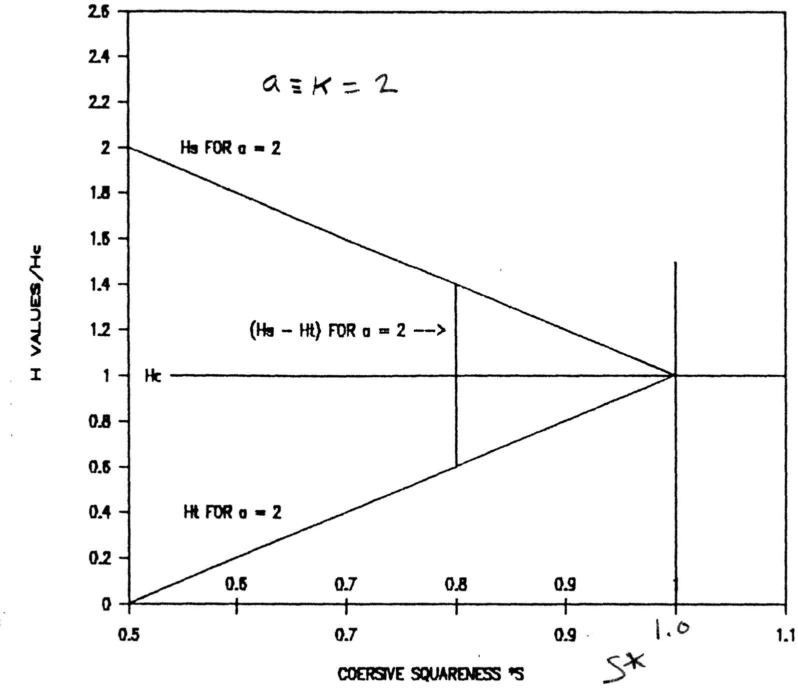
It follows that

$$Hs - Ht = 2 \cdot k \cdot Hc(1 - S^*)$$

where **k** can be selected to have Ht and Hs as close to -Mr and +Mr as desired. For k = 2

$$Hs - Ht = 4 \cdot Hc(\overset{1 - S^*}{\cancel{S^* - 1}})$$

As seen Hs - Ht is highly dependent on S*.



The length of the transition region at any y_1 position could be determined from the constant contour from of the Karlquist equation (5.7) as the difference between x values evaluated at Hx = Hs and Hx = Ht.

$$x^2 + \left[y - \frac{1}{2} \cdot \frac{H_g\, g}{\pi \cdot \tan(Hx)}\right]^2 = \left[\frac{1}{2} \cdot \frac{H_g\, g}{\pi \cdot \tan(Hx)}\right]^2 + (g/2)^2 \qquad (5.7)$$

$$Lt = x(Hs) - x(Ht)$$

From Figure 6.2 the derivative of the Karlquist expression Hx(x,y=y1), equaition (5.9), at Hx = Hc can be written as

$$\left.\frac{dHx(x,y=y1)}{dx}\right|_{H=Hc} \approx \frac{Hs - Ht}{Lt} = \frac{2 \cdot k \cdot Hc(1 - S^*)}{Lt}$$

or

$$Lt = \frac{2 \cdot k \cdot Hc(1 - S^*)}{dHx/dx|_{H=Hc}}$$

dHx/dx is the gradient of the head field at y_1 and at Hx = Hc of the media. Thus the larger the head field gradient the shorter the transition.

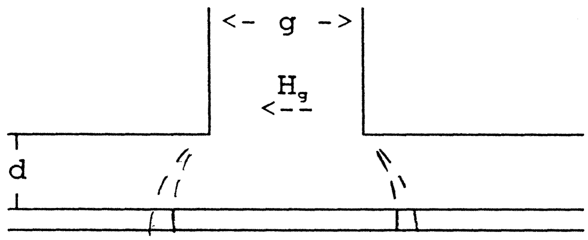
6.3 EFFECTIVE FLYING HEIGHT

The transition as shown in Figure 6.2 is for only one value of y.

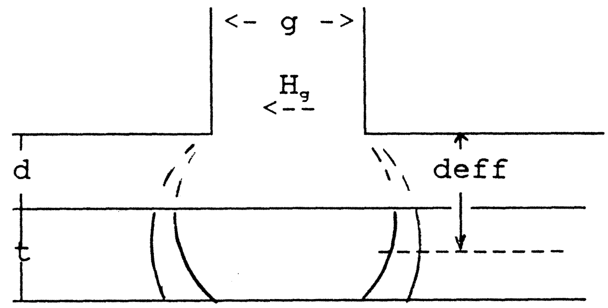
For thin film media where the media thickness t is small compared to g/2 this is a good approximation.

For the 3390 g/2, d and t are all close to 250 nano-meters (nm).
≈ 10 micro inch

t for a film disk where g/2 and d are 250 nm would be about 25 nm.



Thin Film Media



Particulate Media

The additional thickness of the particulate disk adds to the transition width in a complex manner since level farther from the head contribute less to the signal both amplitude and resolution wise.

The effect of disk thickness can be taken into account in an approximate manner by replacing the flying height d with an effective flying height d_{eff} where d_{eff} is the geometric~~al~~ mean of d and t.

$$d_{eff} = \sqrt{d \cdot (d + t)} \tag{6.1}$$

We will use d_{eff} as the y value in the following analyses.

6.4 APPROXIMATE EXPRESSIONS FOR THE TRANSITION PARAMETER

The transition as constructed in Figure 6.2 can be expressed as

CAN USE ARCTAN TRANSITION

$$Mx(x) = M(Hx(x,y))$$

FUNCTION OF HEAD FIELD

The gradient of the magnetization in the region of the transition is

$$\frac{\partial Mx}{\partial x} = \frac{dM(Hx)}{dHx} \cdot \frac{dHx}{dx} \tag{6.2}$$

PARTIAL

To take into account the demagnetizing field in the medium equation (6.2) can be written as

$$\frac{dMx}{dx} = \frac{dM(H_\Sigma)}{dH_\Sigma} \cdot \frac{dH_\Sigma}{dx} \tag{6.3}$$

where H_Σ is the total H field and

$$\frac{dH_\Sigma}{dx} = \frac{dHx}{dx} + \frac{dHd}{dx} \tag{6.4}$$

DEMAGNETIZING FIELD

A complete solution to these differential equations requires iterative numerical methods since dHd/dx is proportional to dMx/dx.

Williams and Comstock present a detailed discussion and derivation for the transition parameter including both demagnetization and the head field and assuming an arctangent transition. An approximation to their complicated expressions that valid over a wide range of parameter values is.

$$a = 3.1 \cdot \left[\frac{Mr \cdot t \cdot d_{eff}}{Hc}\right]^{1/2} \quad \text{or} \quad 1.5 \cdot \left[\frac{Mr \cdot t \cdot d_{eff}}{\pi Hc}\right]^{1/2} \tag{6.5}$$

CGS units MKS units

WILLIAMS COMSTOCK TRANSITION PARAMETER

in contrast to equation (4.11)

$$a_o = a_d = \frac{2 \cdot Mr \cdot t}{Hc} \quad \text{(CGS)} \tag{6.6}$$

Where only the demagnetizing field is included.
Equations (6.5) and (6.6) can both represent the the

transition parameter depending on the value of 4πMr/Hc. CGS

FLUX IN MEDIA

In order to see this we can plot a and a_o each normalized to the medium thickness t vs 4πMr/Hc. We have

$$\frac{a_o}{t} = \frac{2\cdot Mr}{Hc} = \frac{4\pi\cdot Mr}{Hc}\cdot\frac{1}{2\pi} \quad \text{vs} \quad \frac{4\pi\cdot Mr}{Hc} \qquad \text{and}$$

$$\frac{a}{t} = 3.1\cdot\left[\frac{Mr}{Hc}\cdot\frac{d_{eff}}{t}\right]^{\frac{1}{2}} = \frac{3.1}{2\sqrt{\pi}}\cdot\left[\frac{4\pi\cdot Mr}{Hc}\cdot\frac{d_{eff}}{t}\right]^{\frac{1}{2}} \quad \text{vs} \quad \frac{4\pi\cdot Mr}{Hc} \qquad (6.7)$$

Equation (6.7) is plotted for a discrete range of d/t values of 1, √10 and 10 in Figure 6.3

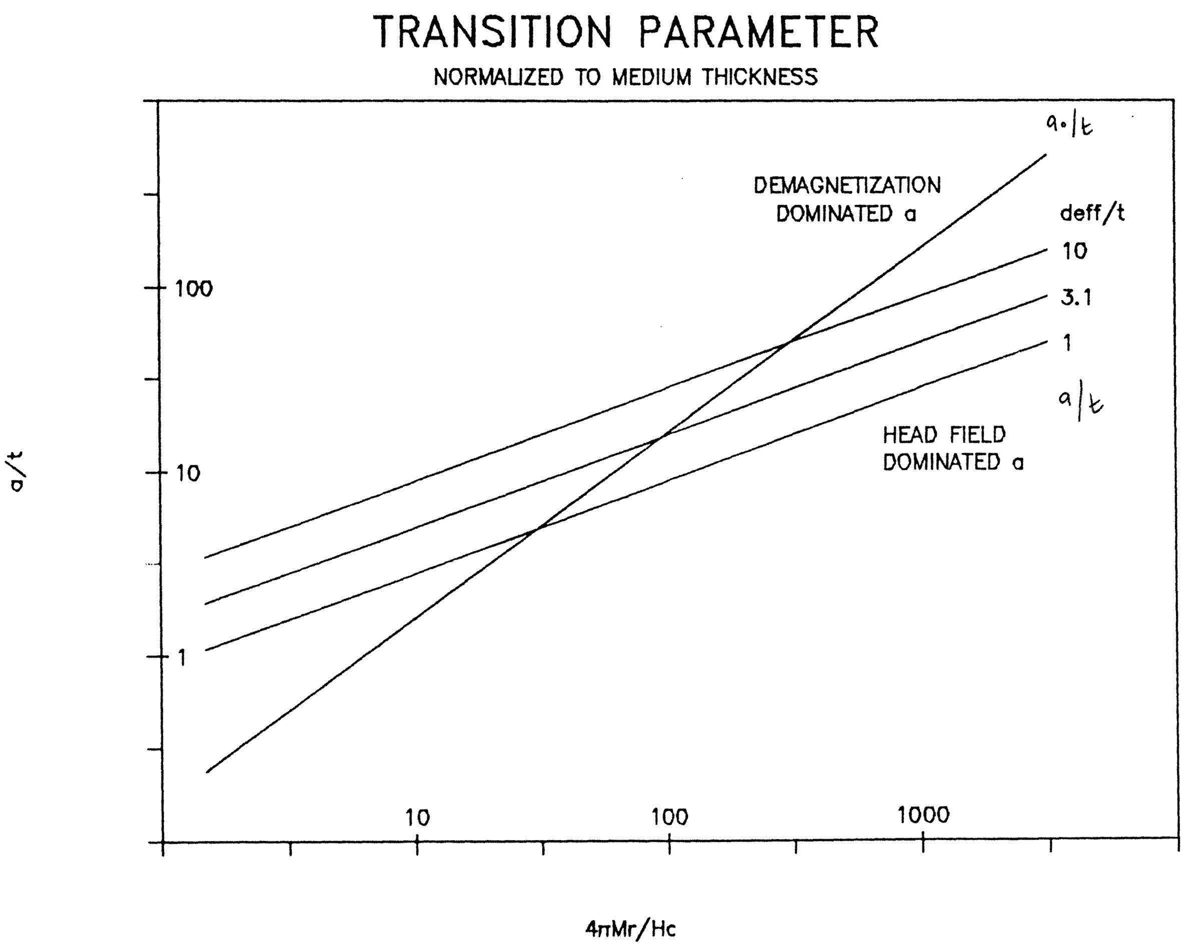


Figure 6.3

For large 4πMr/Hc the demagnetizing field will be large and will dominate the transition parameter. For smaller values of 4πMr/Hc the head field gradient is dominant.

6.5 NUMERICAL EXAMPLES OF TRANSITION PARAMETERS

The numerical value of the transition parameter, **a**, is important in the read process since, as we will later see, it is added directly to d_{eff} in determining the readback signal.

Let's calculate the transition parameter for two cases,

1. The recently announced 3390 (PARTICULATE) and

2. a hypothetical thin film disk with a head similar to that of the 3390.

The pertinent data and resulting calculations are shown in Figure 6.4 and the values for $4\pi Mr/Hc$ and d_{eff}/t are marked on the graph (repeated from Figure 6.3).

For both cases the magnitude of **a** is in the range dominated by the head field. This is in general the case for DASD applications

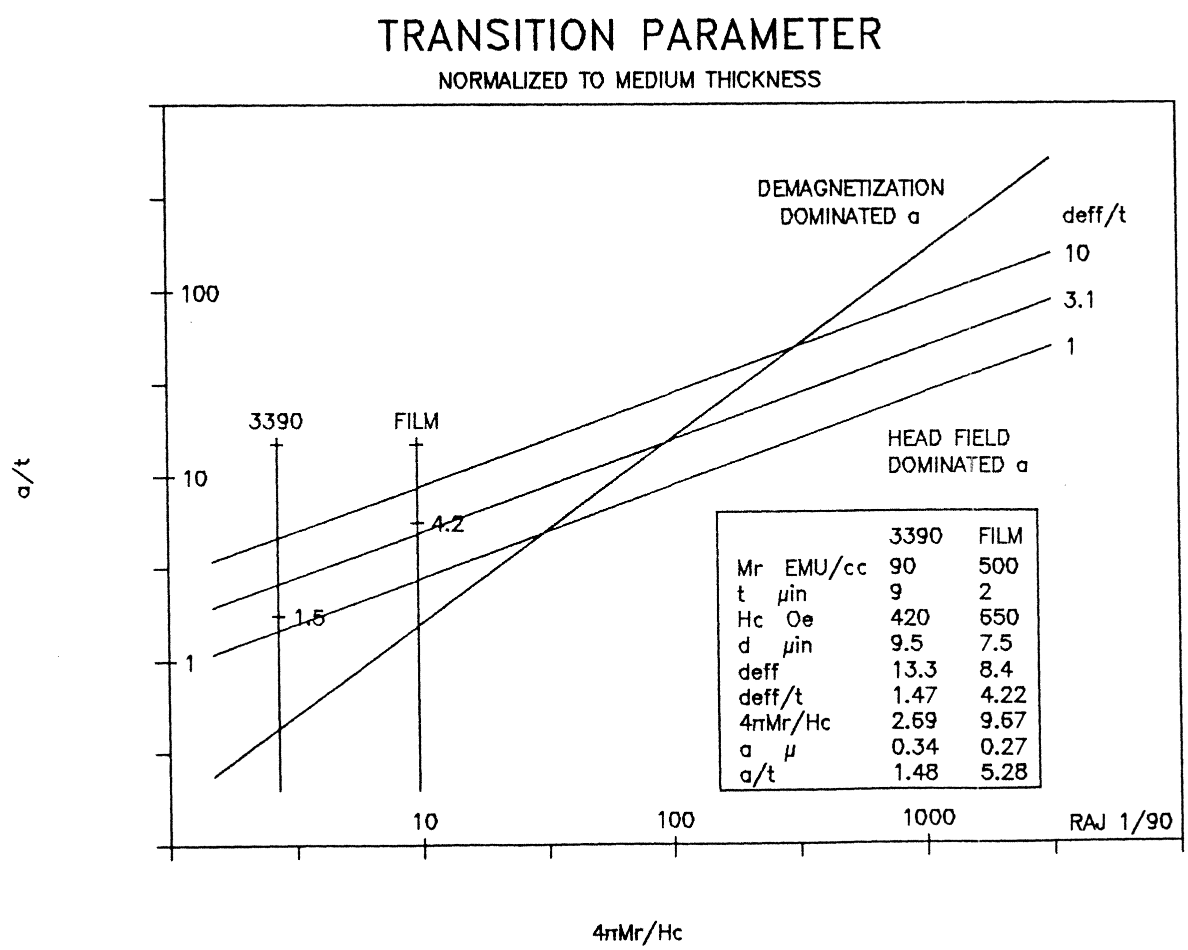


Figure 6.4

The calculation for **a** follows from equations (6.1) & (6.5).

$$d_{eff} = \sqrt{d\cdot(d+t)} \tag{6.1}$$

$$a = 3.1\cdot\left[\frac{Mr\cdot t\cdot d_{eff}}{Hc}\right]^{\frac{1}{2}} \tag{6.8}$$

There are several dimensions used for a, t and d viz. microns, microinches and nanometers. From this point on I am going to standardize on nanometers (nm) but will in some cases will give others in parentheses.

Where t and y = d_{eff} are both in µin, Mr is in EMU/cc and Hc is in Oe, (6.5) can be written as

$$a = 79\cdot\left[\frac{Mr\cdot t\cdot d_{eff}}{Hc}\right]^{\frac{1}{2}}\ \text{nm} \tag{6.9}$$

Where t and y = d_{eff} are both in nm (nanometers), (6.5) is.

$$a = 3.1\cdot\left[\frac{Mr\cdot t\cdot d_{eff}}{Hc}\right]^{\frac{1}{2}}\ \text{nm} \tag{6.10}$$

For the 3390 case

$$d_{eff} = (9.5(9.5+9))^{\frac{1}{2}} = (175.75)^{\frac{1}{2}} = 13.26\ \mu\text{in or } 337\ \text{nm}.$$

$$a = 79\cdot\left[\frac{90\cdot 9\cdot 13.26}{420}\right]^{\frac{1}{2}} = 400\ \text{nm}$$

340nm GRAPHED

For the film disk case

d_{eff} = 8.4 µin or 213 nm and

$$a = 79\cdot\left[\frac{500\cdot 2\cdot 8.4}{650}\right]^{\frac{1}{2}} = 270\ \text{nm}$$

Hc 900 → 300 oe

If Hc for the film disk were increased to 1200 Oe a would be 200 nm.

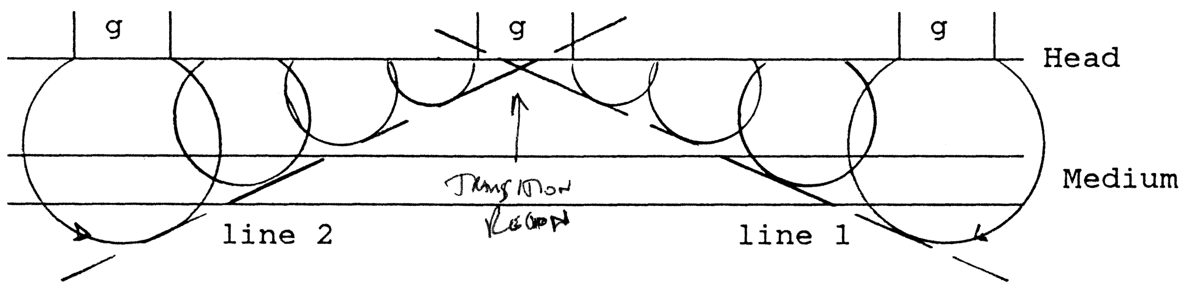
Note that a_0 is comparable in magnitude to d_{eff}.

6.6 THE EFFECTS OF MEDIUM MOTION AND HEAD DELAYS

When the writing current switches polarity the head magnetizing field, Hx(x,y) will reverse.

The inductive nature of the head will result in some finite current rise time and a finite time for Hx to go from +Hs to -Hs.

The problem can be visualized by drawing the Hs contour for a head moving right to left passed a medium as the field reverses.



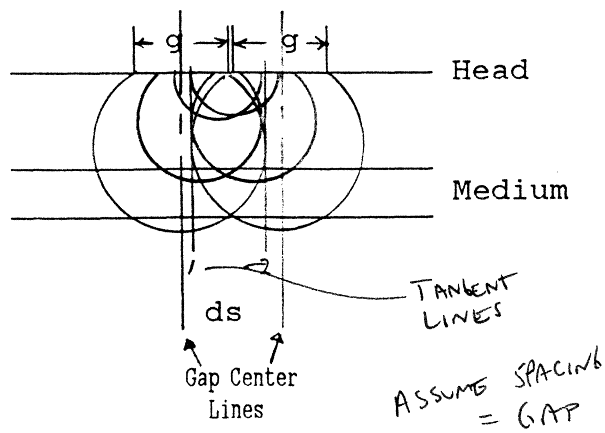
The medium to right of line 1 is magnetized in the + M direction since all of it was subject to a field of +Hs or greater.

The medium to the left of line 2 is magnetized in the - M direction since all of it was subject to a field of -Hs.

The medium between lines 1 and 2 is of uncertain magnetization.

The presence of such uncontrolled regions can introduce noise, distort the transition or even contain another transition~~s~~ if long enough.

The minimum condition required to not have such regions is that the +Hs and -Hs contours intersect at the bottom of the medium as shown.



This condition lends itself to a rigorous solution but an approximate solution is much simpler and provides the required insight and boundary conditions.

The distance moved during the switching time must be less than ds. And ds ≈ g. Thus

$$g \le v \cdot ts \quad \text{or} \quad ts \le g/v$$

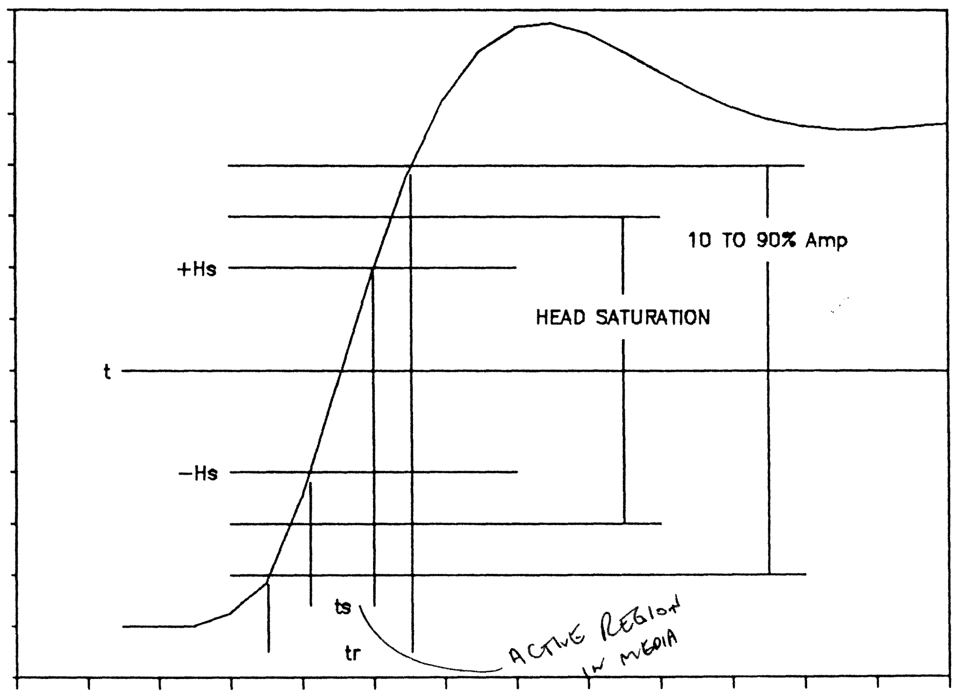
Where v is the velocity and ts is the switching time which is the time for the field to switch from +Hs to -Hs.

For the 3390 the OD velocity is about 57 m/s = 57 ~~mm~~ nm/ns and g is 550 nm. Thus

$$t_s \le 550/57 = 9.6 \text{ ns}$$ SWITCHING TIME

This is about the rise time of the 3390 write current: however, since for the 3390 and in general the switching range of H is greater than -Hs to +Hs and in addition the current drives the head into saturation, ts is less than the current rise time. Thus there is no detrimental effect due to rise time or medium motion.

MEDIA VELOCITY NOT VERY IMPORTANT



SWITCHING CURR

6.7 THE EFFECT OF DEMAGNETIZATION FROM THE LEADING EDGE OF THE GAP

ROSCAMP
KURLAND

The field at any point in the medium is the sum of all of the fields at that point.

Up to now we have considered the head field and the demagnetizing field generated by the transition being written.

There will also be fields due neighboring transitions.

These fields will be weaker than those from the head and the transition being written but their contribution will shift the position of the Hs point resulting in the transition being written early or late.

The closest transition is the one associated with the leading edge of the head gap. However, if the medium was previously magnetized in the direction to which the head field just switched, there is no transition there.

This is illustrated in the example below from Roscomp.

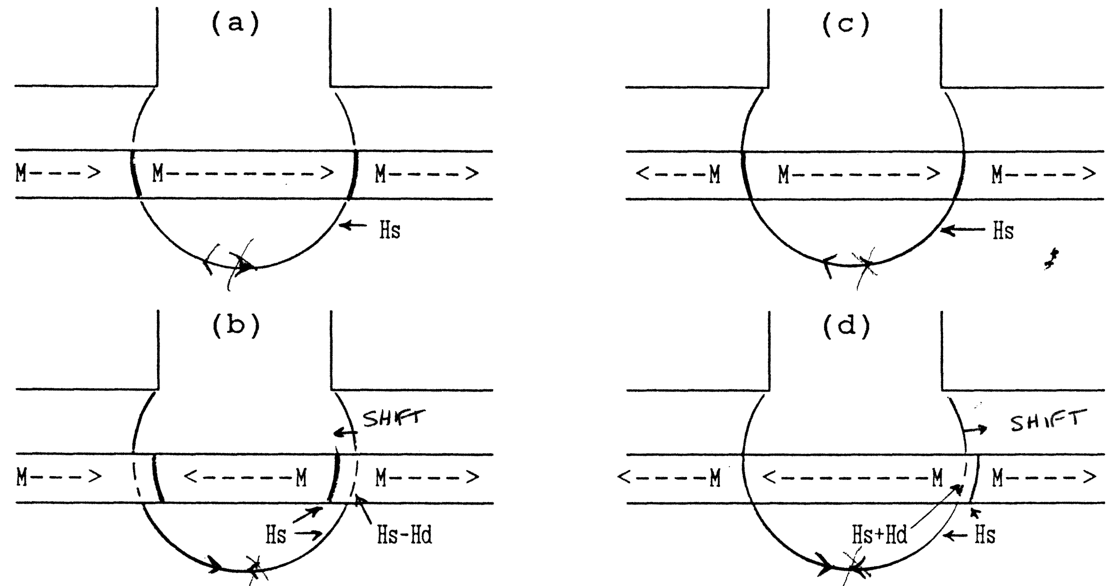


Figure 6.5

In (a) the medium magnetization entering the Hs circle is in the same direction as Hs.

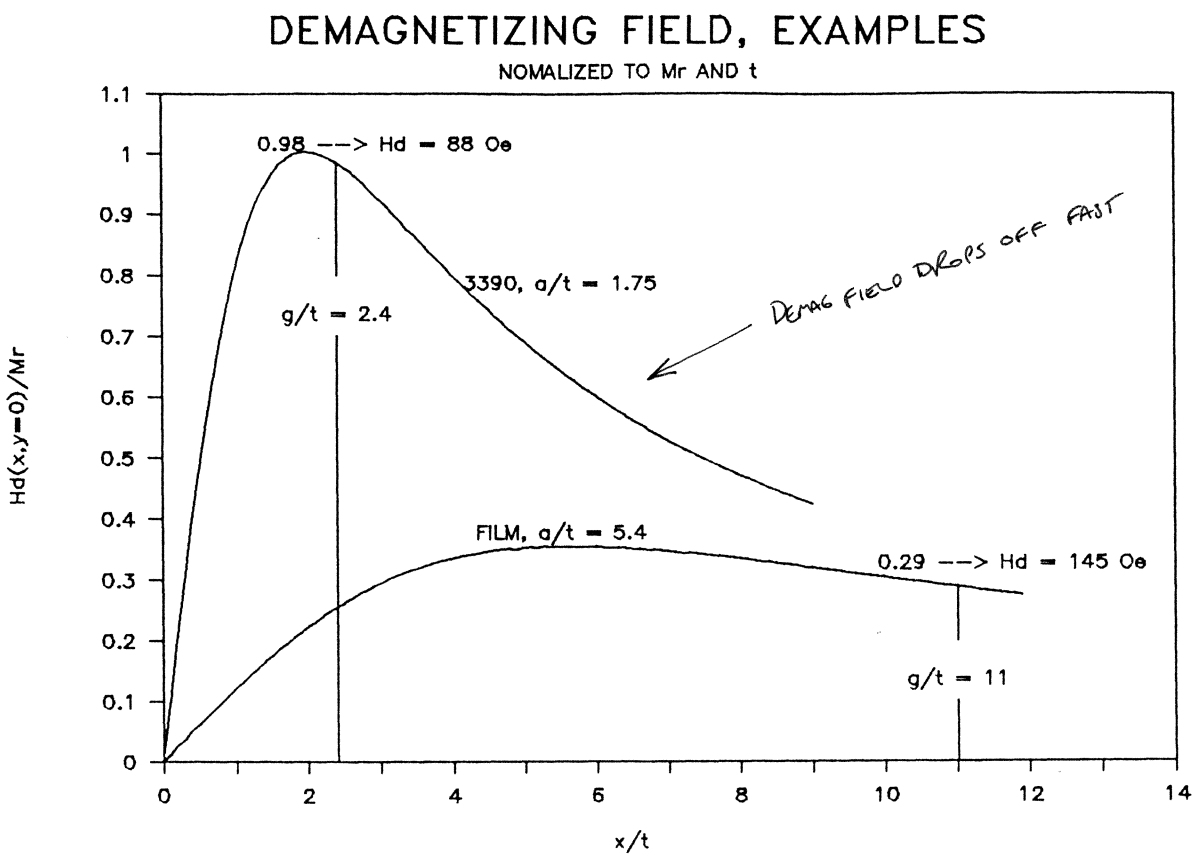
In (b), right after Hs reverses, Hd from the leading transition opposes the head field. Thus the Hs value shifts closer to the gap.

In (c) the medium magnetization entering the Hs circle is in the opposite direction of Hs.

In (d), right as Hs reverses, there can be some effect from the leading transition as it is reversed. This effect in the same direction as the new field and thus shifts the trailing transition way from the gap. The magnitude of Hd from the leading edge of the gap can be calculated from equation (4.9). It is, however, more instructive to use the associated figure on page 4.7.

Let us calculate the values of Hd from the leading edge of the gap Hd for the 3390 and the previous film disk cases.

The figure on page 4.7 is repeated here but with the values for a/t of 1.7 and 5.4 corresponding to those for the 3390 and the film disk example.



x/t becomes g/t and is 2.4 and 11 for the 3390 and film disk cases respectively.

Hd/Mr is greater for the thicker disk by .98/.29 = 3.4 times but since Mr of the film disk is 500/90 = 5.6 times greater than Mr of the particulate disk, Hd of the film disk is 145/88 = 1.7 times greater.

The values of Hd from the leading edge of the gap are not insignificant compared to Hc or Hs.

The value of the shift can be obtained form the Karlquist expression. Larger head field gradient will yield less shift for the same Hd.

MUST SWITCH Hc+Hd FOR GOOD OVERWRITE

6.8 DEMAGNETIZATION FROM PREVIOUSLY AND JUST WRITTEN TRANSITIONS

In addition to the transition at the leading edge of the gap, the demagnetizing field from other transitions can also cause shifting of the transition being written.

For example the contribution of demagnetizing field from a string of n just written transitions at a constant spacing of x_1 would be found by superposition of equation (4.9)

$$Hd = Hx(x_1) - Hx(2 \cdot x_1) + Hx(3 \cdot x_1) - \ldots + Hx(n \cdot x_1)$$

LESS SIGNIFICANT →

If the spacing (and phasing) of the transitions entering the write zone is know, a similar expression can be written.

Making such calculations requires a complex model and is only if interest for special studies and to gain insight.

The effect of previously and just written transitions is less than that of the leading edge of the gap since in general x_1 is greater than g.

Shifts due to these transitions can be of significance, especially at high linear density in film medium of high Mr•t. As ~~we have~~ Hd increases with both Mr and t. WANT LOW Mr·t

UNFORTUNATELY IT GIVES LOW AMPLITUDE

These shifts are of a nonlinear nature and can be a source of detection errors.

6.9 THE EFFECT OF HEAD PRESENCE ON DEMAGNETIZATION

The discussion of demagnetizing fields is not complete without considering the effect of the presence of a high μ material very close to the medium surface. I.e. the recording head.

The head provides a parallel low reluctance path for the demagnetizing fields from within the medium.

The effect is to decrease the total demagnetizing field at the location of the transition being written.

Thus the shifts will be less than predicted by the considerations above but will still be of consequence.

It can also be shown that the transition length due to self demagnetization will be less when the head is present.

The effect of the head can be handled analytically by assuming the head is a magnetic ground plane with image charges.

A complete write model must include the effect of the image charges.

This is illustrated in Figure 3 from Bloomberg shown here and in Figure 4 from Roscamp shown in the next section (6.8).

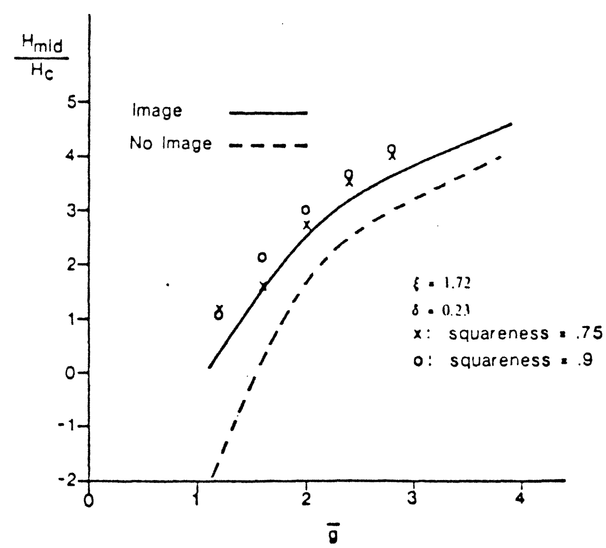


Fig. 3 Variation of H_{mid} with gap length, for given reduced coercivity and applied field. Analytical model gives solid and dashed lines; discrete points are from self-consistent calculation. In an actual bubble, H_{mid} is always positive. Model is always conservative, closely approaching actual bubble near onset of saturation.

6.10 DEMAGNETIZATION AND OVERWRITE

Overwrite is a measurement of how well a previously written pattern is erased by a new pattern.

Experiment, as well as analysis, shows that the poorest overwrite is for the highest data frequency written over the lowest data frequency.

The overwrite measurement is the ratio of the amplitude of the readback signal of the low frequency when originally recorded to that after it is recorded over by the high frequency.

The measurement is made with a spectrum analyzer and expressed in dB. A high absolute value is goodness.

Minimum acceptable overwrite will be a function of the relative magnitude of other error sources for a particular product.

The minimum acceptable value or spec is in the neighborhood of 25 dB.

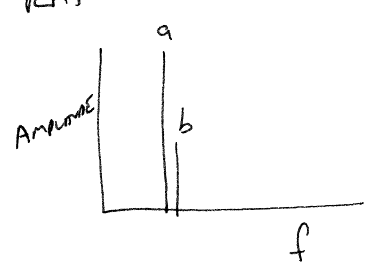
Overwrite can result from inadequate saturation of the medium and from track misregistration between successive read and write operation. These are not the primary sources.

The primary cause of the presence of the low frequency after being written over is amplitude and frequency modulation resulting form the position shifts of the new transitions caused by the previously recorded pattern and the leading edge of the gap.

1,7 4 : 1

2,7 $\frac{8}{3}$: 1

RATIO OF HIGH TO LOW FREQUENCY



WORRY ABOUT OVERWRITE AT OD
(HEAD FLIES HIGHER)

OVERWRITE = $20 \log \frac{a}{b}$

To see this consider three full cycles of 2,7 code low frequency with high frequency overwritten.

Applying the process shown in Figure 6.5, the transitions of the high frequency are shifted left or write of the ideal location.

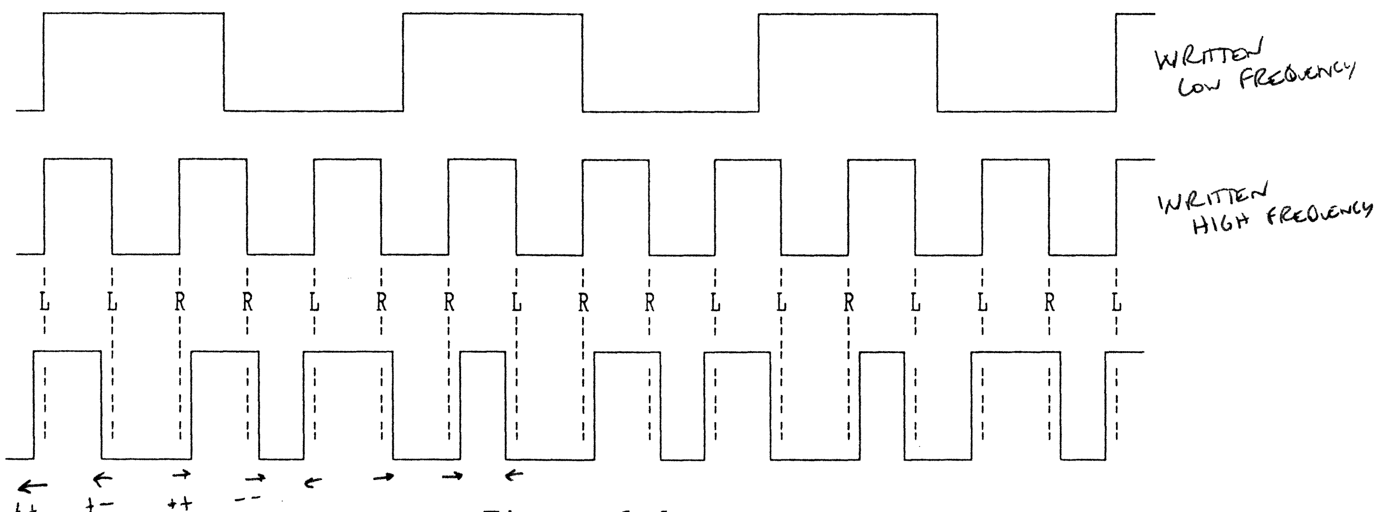


Figure 6.6

The actual shifts will not be as large as shown in Figure 6.6 nor will they all be equal.

The Fourier transform of the resulting readback signal has a significant component of the low frequency as well as sum and difference components.

The magnitude of this low frequency component is the residual low frequency of the overwrite measurement.

The contribution to overwrite from the amplitude and frequency (timing) effects of the transitions shifts is shown in Figure 4 of Roscamp also shown here.

Also note the effect if the image charges in the head are neglected.

The transition shifts and the low frequency component will decrease as the gap increases (lower Hd) and as the head field and head field gradient increase.

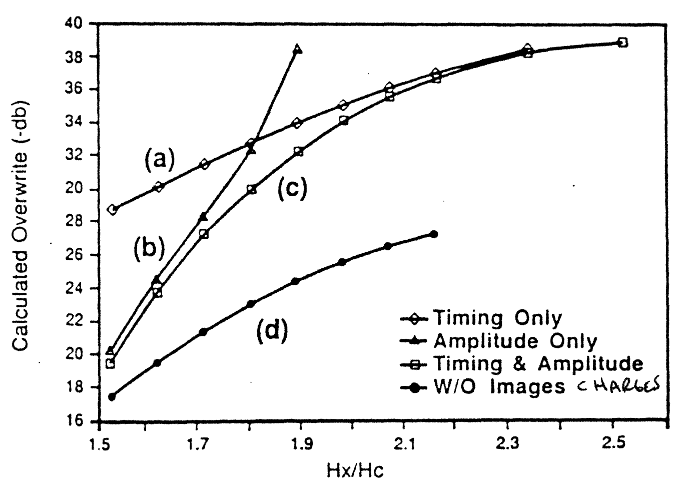


Figure 4 Calculated overwrite vs. maximum applied field at the medium considering a) only timing asymmetry; b) only amplitude modulation; c) both; d) without image charges.

6.11 WRITE FACTOR

Write factor, Kw, is defined as the ratio of the head field at ~~the bottom of the media~~ d_{EFF} to the coercivity.

The head field in the medium must also include the demagnetizing fields. I.e. the maximum Hd should be subtracted from the head field.

$$Kw = \frac{Hx(0, y=\overset{d_{EFF}}{\cancel{d+t}}) - Hd}{Hc} \qquad (6.11)$$

MORE CORRECT

Sometimes the total Hd is added to the coercivity.

$$Kw = \frac{Hx(0, y=\overset{d_{EFF}}{\cancel{d+t}})}{Hc + Hd} \qquad (6.12)$$

Kw is of value for comparing the write conditions for different head geometries, flying heights and disk parameters.

Hs as earlier defined was for illustration purposes. The write factor is of more practical value.

In spite of all of the analysis of earlier sections overwrite as a function of write factor is usually determined experimentally.

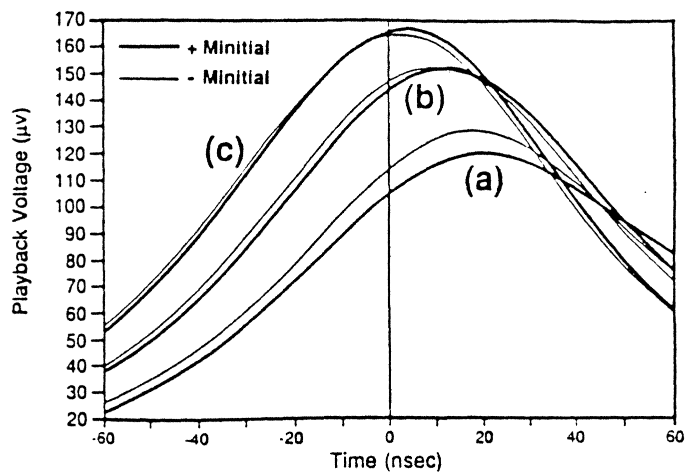
The relationship of Kw to overwrite will depend on a number of factors such as S*, total demagnetizing field etc.

Typically the minimum required write factor is 2.5 or greater. (FILM)

The effect of increasing head field on the amplitude and timing effects of poor overwrite are shown in Figure 2 of Roscamp also shown here.

± 10% ALL OTHER PARAMS

± 15% FLYING HEIGHT



(a) Hx=1.6*Hc (b) Hx=2.0*Hc (c) Hx=2.5*Hc

Figure 2 Isolated readback waveforms for initially positively and negatively d.c. erased media for maximum values of the head field at the medium of a) 1.6*Hc, b) 2.0*Hc and c) 2.5*Hc.

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PROBLEMS

Problem 6.1

Stating with the equations for Hs and Ht derive the expression for Hs - Ht on shown page 6.8.

Problem 6.2

For the 3390 and film disk examples of Figure 6.4 work out the values for d_{eff}, and a for the given values of Hc, t and d.

Problem 6.3

For the 3390 and film disk examples of Figure 6.4 work out the values of the demagnetizing field form the the leading edge of the gap.

Problem 6.4

What is the write factor at the ID for the 3390

a. ignoring the gap demagnetizing field.

b. including the gap demagnetizing field.

7. THE READ PROCESS

7.1 OVERVIEW

The objective of the readback process is to reproduce the write current wave form.

This is a two part process:

1. The readback process where a signal is produced from the transitions in the medium and
2. The detection process where the readback signal is transformed in to a binary train of clocked data.

The detection process is required because the readback signal is:

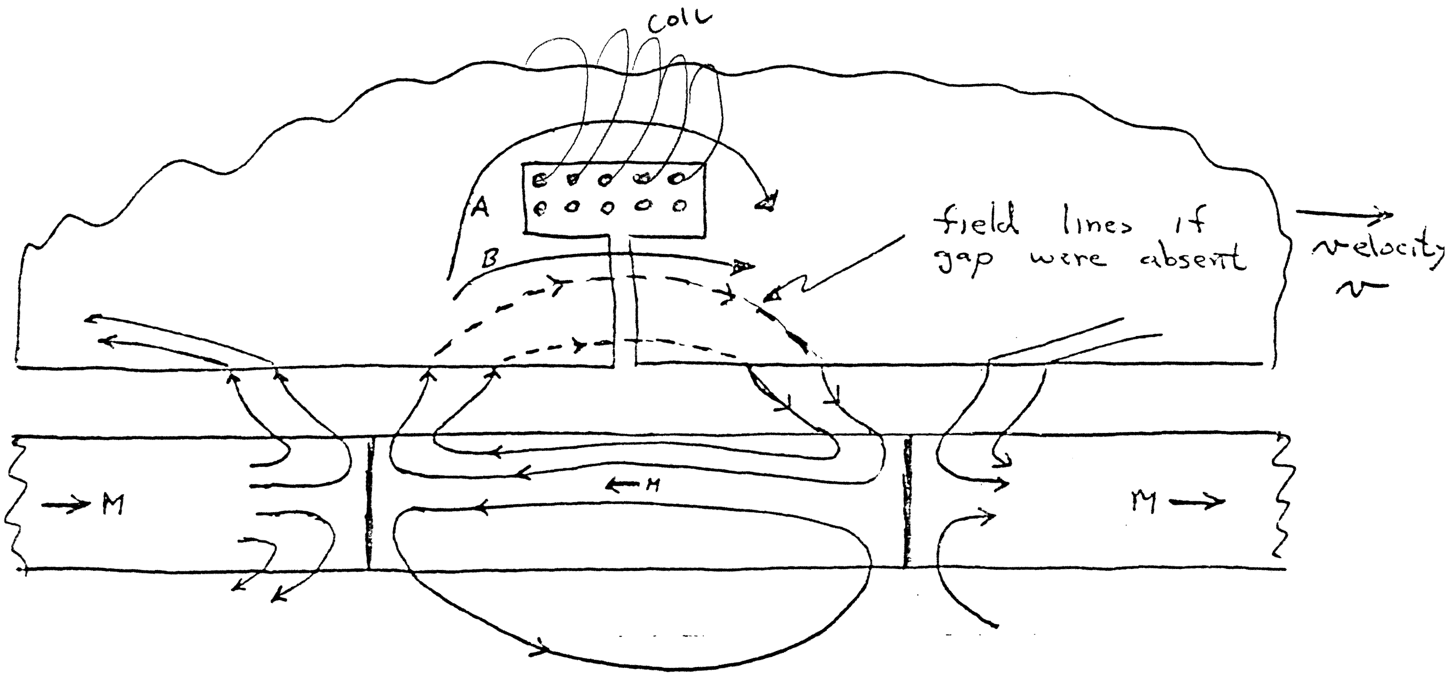
1. The derivative of the write current. Each transition of the write current produces a pulse on readback.
2. It is analog with a large range of pulse amplitudes due to resolution losses and has no DC content.
3. The timing of the readback pulses is unknown and variable. Thus it must produce its own clock.
4. The readback signal also contains noise and interferences.

While the write process is complex and nonlinear, the read process is relatively straight forward and linear.

In this chapter we concentrate on the first step, producing a signal from the transitions in the medium.

The field from the transitions is picked up by the reading head and transduced to an output voltage.

Calculating the fields from the medium that are picked up by the head is, however, not an easy task. The figure below shows the fields in a head from two transitions.



The field in an long solid slab of high μ material very close to the medium can be calculated without too much difficulty.

The problem is in handling the gap and pole tips with finite and varying shapes.

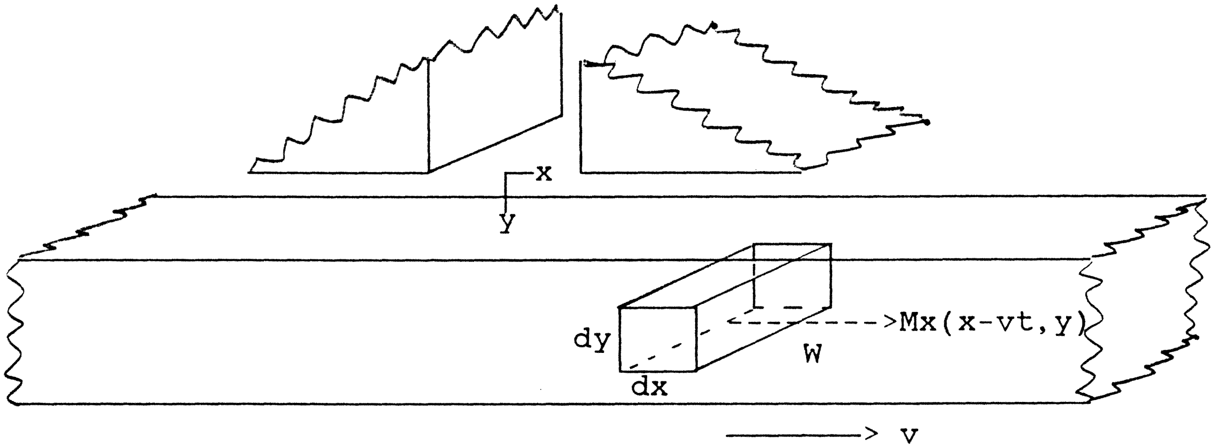
A means of overcoming these difficulties is by use of the reciprocity theorem.

The idea behind the reciprocity theorem as applied to magnetic recording is that is equivalent to calculate the field from a head, when its coil is energized with current, at a point outside the head as to calculate the field inside the head due to a point charge of Qm = -del•M located at the point outside the head.

7.2 READBACK VOLTAGE CALCULATED WITH RECIPROCITY THEOREM

Consider a head with an horizontal field below the gap of Hx(x,y) per unit of N•I

Also consider a small volume element in the magnetic magnetized medium of dx by dy by W.

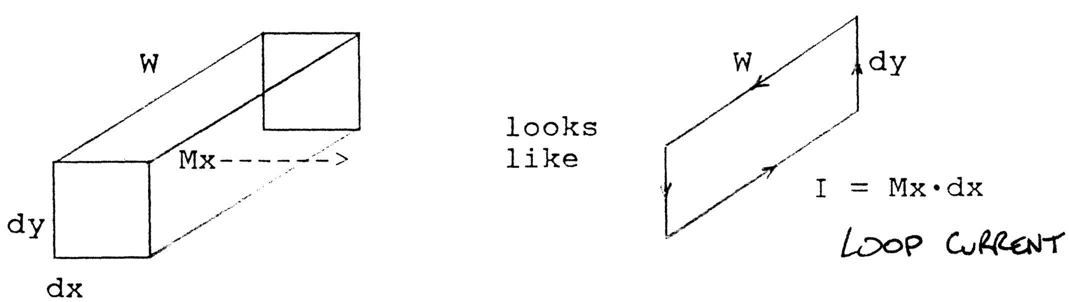


v•t can be called x´where x´ is referenced to the medium and is the shift of the element referenced to x = 0.

x´ = v•t Where t in this case is time.

Since $M = \dfrac{m}{\text{unit V}} = \dfrac{I}{\text{unit L}} = Js$ (See page 1.6)

The volume element

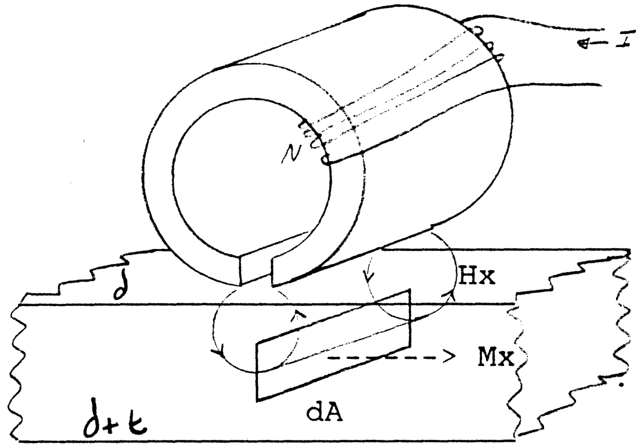


Thus $M \cdot dx = Js \cdot dx = I_{loop} = Mx(x-x',y)dx$

M VARIES THROUGH MEDIUM

The key to the application of reciprocity in this case is mutual inductance.

Mutual inductance between two coils arises when some magnetic flux is common to two coils.

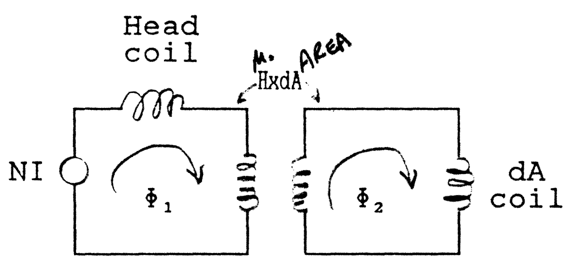


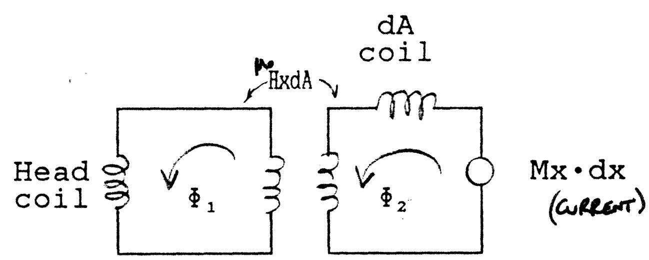
In our case the two coils are the coil in the head and the coil in the medium carrying the current Mx•dx.

Remember from chapter 5 on magnetic circuits

NI α voltage and Φ (flux) α current. A magnetic ciruit for the two coils and the common flux linkage is.

PROPORTIONAL





$\Phi_2 = NI \cdot \mu_o HxdA$

WRITE

$\Phi_1 = Mxdx \cdot \mu_o HxdA$

READ

USEFUL TO CALC STRENGTH OF FIELD

Since $dA = W \cdot dy$

WIDTH OF COIL

$\Phi_1 = \mu_o \cdot W \cdot Hx \cdot Mx \cdot dx \cdot dy$

The flux in the head coil due to all of the volume elements is found by integrating over the total volume.

$$d\Phi_{head} = \mu_o \cdot W \cdot \int_{-\infty}^{\infty} dx \int_{d}^{d+t} dy \; Hx(x,y) \cdot Mx(x-x',y) \qquad (7.1)$$

The readback voltage is $d\Phi/dt$ through each of N coil windings. Thus

$$V(x) = N \cdot \frac{d\Phi}{dt} = N \cdot \frac{d\Phi}{dx'} \cdot \frac{dx'}{dt} = N \cdot v \cdot \frac{d\Phi}{dx'} \qquad (7.2)$$

VELOCITY

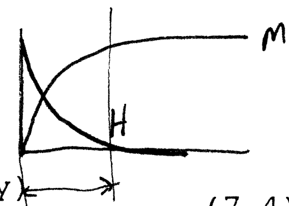
Combining equations (7.1) and (7.2)

A/m   A/M   CONVOLUTION

$$V(x) = N\cdot v\cdot W\cdot \mu_0 \int_{-\infty}^{\infty} dx \int_{d}^{d+t} dy\ Hx(x,y)\cdot \frac{dMx(x-x',y)}{dx'} \tag{7.3}$$

This is a convolution integral and is in MKS units. SHOW $4\pi 10^{-8}$ IS CONVERSION FACTOR END UP WITH VOLTS

dM/dx′ is the one dimensional divergence of M and only has a nonzero value in the vicinity of a transition. (See page 4.3.)



In CGS units

$4\pi \cdot 10^3$ EMU CC

$$V(x) = 4\pi\cdot N\cdot v\cdot W\cdot 10^{-8} \int_{-\infty}^{\infty} dx \int_{d}^{d+t} dy\ Hx(x,y)\cdot \frac{dMx(x-x',y)}{dx'} \tag{7.4}$$

OE

$\frac{dMx}{dx}$ IS ONLY OF INTEREST IN TRANSITION REGI

Where V is in Volts, M in EMU/cc and distances in cm.

The y integration is ≈ to evaluating Hx and M at $y = d_{eff}$.

Mx and Hx can now be any function we please. Mx can be a step, a ramp, an arctangent or even sinusoidal. Hx can be from any shaped head for which ~~it~~ Hx can be determined.

If Hx is the Karlquist arctangent function and Mx is also assumed to have an arctangent form, it can be shown that evaluating the convolution integral is equivalent to evaluating Hx at

$$y = y_0 = d_{eff} + a \tag{7.5}$$

Thus the readback pulse can be found directly form the head sensitivity function.

This process leads to

$$V(x) = 8\pi\cdot 10^{-8}\cdot N\cdot v\cdot W\cdot Mr\cdot t\cdot Hx(x,y_0) \tag{7.6}$$

The Hg/π coefficient of the the Karlquist expression will be, from equation, (5.4) $\varepsilon/g\pi$ since the NI factors are already in equation (7.6).

$$H_g = \frac{NI}{g}\varepsilon$$ EFFICIENCY

V(x) for a single transition and will be an isolated pulse.

The readback process is linear and consequently the pulse train from a number of transition at various spacings can be created by superposition of the isolated pulse.

Superposition will be valid until densities are reached where the nonlinear transition shifts in the write process become a factor.

We will discuss this further in the section on equalization.

The peak amplitude for a Karlquist head is found from (7.6) with x = 0.

$$Vb\text{-}p = 8\pi \cdot 10^{-8} \cdot N \cdot v \cdot W \cdot Mr \cdot t \cdot \frac{2\varepsilon}{\pi g} \cdot \tan^{-1}\left(\frac{g/2}{y_o}\right)$$

$$Vb\text{-}p = 16 \cdot 10^{-8} \cdot N \cdot v \cdot W \cdot Mr \cdot t \cdot \frac{\varepsilon}{g} \cdot \tan^{-1}\left(\frac{g/2}{y_o}\right) \qquad (7.7)$$

It is useful to define what is sometimes referred to as head sensitivity i.e. V(x)/W or the output voltage per micron of track width.

I would rather call this pulse sensitivity (Ps) since V/W or Ps is only partly dependent on the head. Equation (7.7) can be written as

INCLUDES GAP, FLYING HEIGHT, VELOCITY

$$Ps = \frac{Vb\text{-}p}{W} = \underbrace{\left(\frac{N \cdot \varepsilon}{g}\right)}_{\text{HEAD}} \cdot \underbrace{\left(\tan^{-1}\left(\frac{g/2}{y^o}\right) \cdot v\right)}_{\text{SYSTEM}} \cdot \underbrace{(Mr \cdot t)}_{\text{DISK}} \cdot 16 \cdot 10\text{-}8 \qquad (7.8)$$

ACCURATE FOR INDUCTIVE HEADS

As can be seen Ps is a function of head, disk and what I called system parameters. The arctangent factor contains parameters from all three, viz. g from the head, Mr, t and Hc from the disk and d which is system.

In summary the parameters are:

Head:

- g head gap
- N number of turns
- ε head efficieny
- W head width

Disk:

- M_r remanent magnetization
- t thickness
- H_c coercivity

System:

- v meduim velocity
- d head to medium spacing

PROBLEMS

Problem 7.1

The expression for the b-p output voltage, (7.7) has the value of the read gap in several places viz.

$$\varepsilon/g \cdot \tan^{-1}\left(\frac{g/2}{y_o}\right)$$

where ε is of the form

$$\varepsilon = \frac{1}{1 + k/g} = \frac{g}{g+k}$$

In order to see the sensitivity of the readback voltage to g plot the following as functions of g for g = .1, .2, ... 1 microns.

$$\frac{1}{g} \cdot \tan^{-1}\left(\frac{g/2}{y_o}\right)$$

$$\varepsilon$$

$$\varepsilon \cdot \frac{1}{g} \cdot \tan^{-1}\left(\frac{g/2}{y_o}\right)$$

for y_o = 600 nm and ε = .85 when g = .6 μ. FIND K

Problem 7.2

Calculate the readback voltage for the 3390 assuming: N = 31, v = 31 m/s, W = 8 microns, Mr = 90 EMU/cc, t ≈ d = 9 μin and g = .55 μ, Hc = 420 Oe. and ε is as in problem 7.1.

8. THE THIN FILM HEAD

8.1 THIN FILM HEAD & DISK PARAMETERS

The figures on pages 5.3 and 5.8 show the structure of the core and pole tips of a typical thin film head. The figure below shows the key dimensions and magnetic parameters that we will use for functions involving the thin film head.

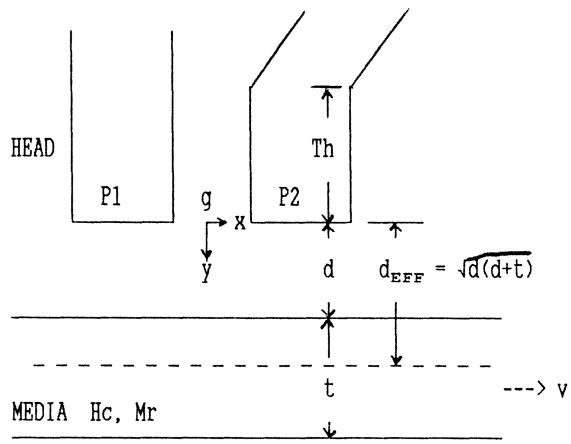


Figure 7.1

One of the primary difference between the thin film and ferrite head is that the thin film head has finite pole tips where as the ferrite head head has, for all practical purposes, semi-infinite pole tips.

8.2 THE SZCZECK FIELD EXPRESSIONS FOR THE FINITE POLE TIP HEAD

The Karlquist expression matches the ferrite head.

The field function for the thin film head is a superpostion of the Karlquist expression for the gap plus expressions for the pole tips.

The pole tip expressions were worked out by Ted Szczeck by a combination of theoretical and ~~i~~mperical methods. The imperical methodes involved measuring fields around large scale head models.

The pole tip expressions are quite long as shown below.

KARLQUIST TERM

$$H_x(x,y) = \frac{H_g}{\pi}\left[\mathrm{Atan}\left(\frac{g/2+x}{y}\right) + \mathrm{Atan}\left(\frac{g/2-x}{y}\right)\right] \qquad \text{(Remember, Hg per unit NI in read mode is } \varepsilon/g\text{)}$$

SZCZECK POLE TIP TERMS

$$-\frac{.59\cdot g\cdot H_g\cdot y}{2\pi}\left[\frac{1}{y^2+(P_1+g/2-x)^2} + \frac{1}{y^2+(P_2+g/2-x)^2}\right]$$

$$+\frac{gH_gP_1}{4\pi}\left[\frac{(x-g/2)^2-y^2}{[(x-g/2)^2+y^2]^2}\left[\mathrm{Atan}\left(\frac{P_1+g/2-x}{y}\right)-\frac{\pi}{2}\right] - \left[\frac{(P_1+g-2x)\cdot y}{[(x-g/2)^2+y^2][y^2+(P_1+g/2-x)^2]}\right] + \left[\frac{y\cdot(x-g/2)}{[(x-g/2)^2+y^2]^2}\ln\left[\frac{P_1^2}{y^2+(P_1+g/2-x)^2}\right]\right]\right]$$

$$+\frac{gH_gP_2}{4\pi}\left[\frac{(x-g/2)^2-y^2}{[(x-g/2)^2+y^2]^2}\left[\mathrm{Atan}\left(\frac{P_2+g/2-x}{y}\right)-\frac{\pi}{2}\right] - \left[\frac{(P_2+g-2x)\cdot y}{[(x-g/2)^2+y^2][y^2+(P_2+g/2-x)^2]}\right] + \left[\frac{y\cdot(x-g/2)}{[(x-g/2)^2+y^2]^2}\ln\left[\frac{P_2^2}{y^2+(P_2+g/2-x)^2}\right]\right]\right]$$

Figure 7.2 shows the Karlquist gap function, the sum of the poletip functions and the total Szczeck finite pole tip head, field function.

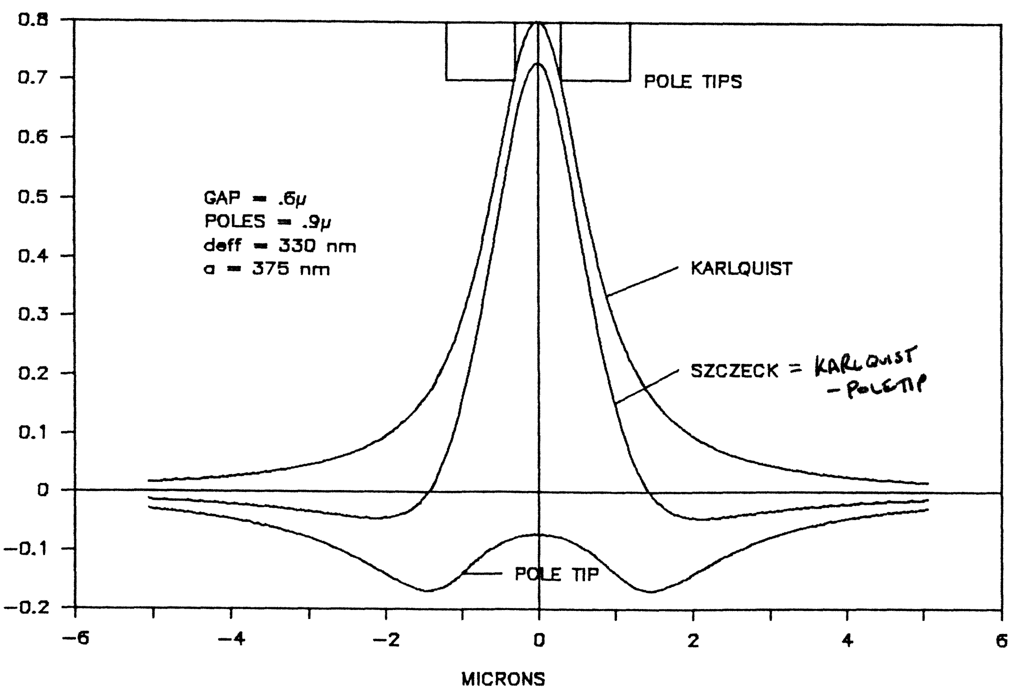


Figure 7.2

Note that the peak amplitude is essentially the Karlquist term. Consequentally one may use equation (7.7) for Vb-p with little error.

References:

1. T. J. Szczeck, IEEE Transactions on Magnetics, Vol. Mag-15 1979 (1319

9. NOISE, SNR AND ERROR RATE

9.1 NOISE AND INTERFERENCE

Noise in the magndtic channel is caused by random processes in the:

N_a Electronics and circuits

N_h Heads

N_d Media

Interferences come from

Old information

Overwrite

OI due to track misregistration (tmr)

Intersymbol interferrence

Adjacent track data

Stray magnetic fields

Radio frequency interference (rfi)

In this section we will focus on the noise characteristics of each of the sources, how they combine to yield a SNR and how this translates to an error rate.

9.2 SIGNAL TO NOISE RATIO (SNR) DEFINITIONS

There are two definitions commonly used for SNR in disk magnetic recording. They are:

rms hi frequency signal/rms noise and

low frequency base to peak signal/rms noise.

The first matches the classical signal power to noise power definition for SNR.

The high frequency readback signal is approximately sinusoidal. This definition is useful for checking the potential error rate performace of a head and disk against a given density specification with a given detection system.

However, it is not sufficient since it confounds signal amplitude and resolution.

The second is better for individual component specification and development and system design purposes since it does not confound SNR and resolution as does the first.

The required minimum resolution for various detection systems varies from 85% to below 50%.

I will primarily use the second definition.

$$SNR = 20 \text{ LOG} \left(\frac{\text{SIGNAL}_{\text{RMS}}}{\text{NOISE}_{\text{RMS}}} \right)$$

$$RMS = \frac{\text{PEAK-TO-PEAK}}{\sqrt{2}}$$

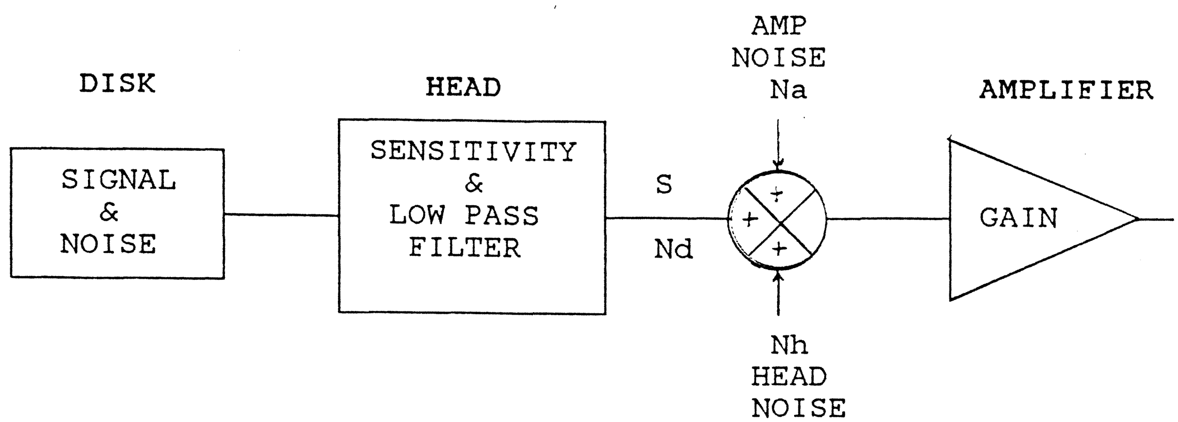
9.3 MAGNETIC CHANNEL NOISE CIRCUIT

The disk, head and amplifier noises are best handled by suming them at the input to the first amplifier stage.

This is generally a preamp located as close as possible to the head so as to minimize the pick up of interferences in the wir~~er~~ing to the head.

The characteristics of a good preamp are to have low noise and a high enough gain so that the noise and interference pick up of subsequent stages is small compared to the amplified noise coming out of the preamp.

A block diagram of the channel noise sources is shown below.



Σ Noise = $\sqrt{Nd^2 + Nh^2 + Na^2}$ at the input to the amplifier RMS NOISE (9.1)

$$SNR = \frac{Signal}{\sqrt{Nd^2 + Nh^2 + Na^2}} \quad (9.2)$$

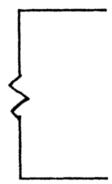
Before going any further with this equation, let's examine each of the contributing noises, Nd, Nh and Na.

AS HEAD SENSITIVITY INCREASES, SO DOES DISK NOISE & SIGNAL

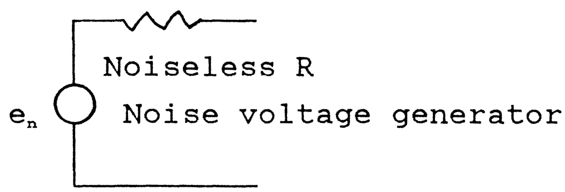
9.4 JOHNSON OR THERMAL NOISE -- DOMINANT NOISE OF HEADS

Any energy absorbing device has random noise associated with it.

For this discussion the source of johnson noise is resistance.



Noise equivalent ckt of R is



e_n is the rms noise voltage = $\sqrt{4KTBR}$

K = Boltzmann's constant = 1.38 E-23 J/degree Kelvin

T = temperature in degrees kelvin

B = Bandwidth in Hz

R = resistance value in Ohms

Noise voltages add in rms fashion -- sources are uncorrelated.

$$e_{nT} = \sqrt{e_{n1}^2 + e_{n2}^2 + .. + e_{nN}^2}$$

Johnson noise is Gaussian and white.

I.e. peak amplitudes have gaussian distribution about the mean and the frequency response is flat.

9.5 HEAD NOISE

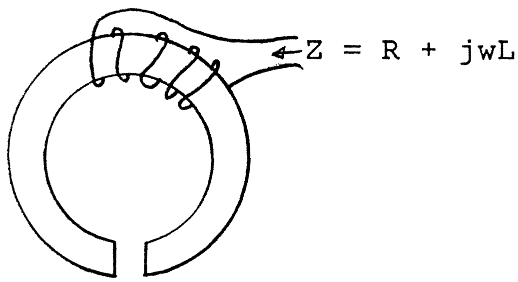
Heads have various loss mechanisms which can be represented as resistors in an equivalent circuit. These all produce johnson noise.

Winding resistance

Eddy currents in metal, $R \propto \sqrt{f}$

Domain wall damping

Below resonance the head is resistive and inductive.



$$L = \frac{N\Phi}{I} = \frac{N \dfrac{NI}{\text{Gap + Coil Reluctances}}}{I} = \frac{N^2}{\text{Gap + Coil Reluctances}}$$

$$L = \frac{N^2}{\dfrac{g}{\mu_o A_{Gap}} + \dfrac{l_{core}}{\mu_o \mu A_{COIL}}}$$

ℓ = length
g = Gap length
A = Area

μ is complex = $\mu' - j\mu''$

Both μ' and μ'' are functions of frequency.

LOSS FUNCTION AS FREQ INCREASED

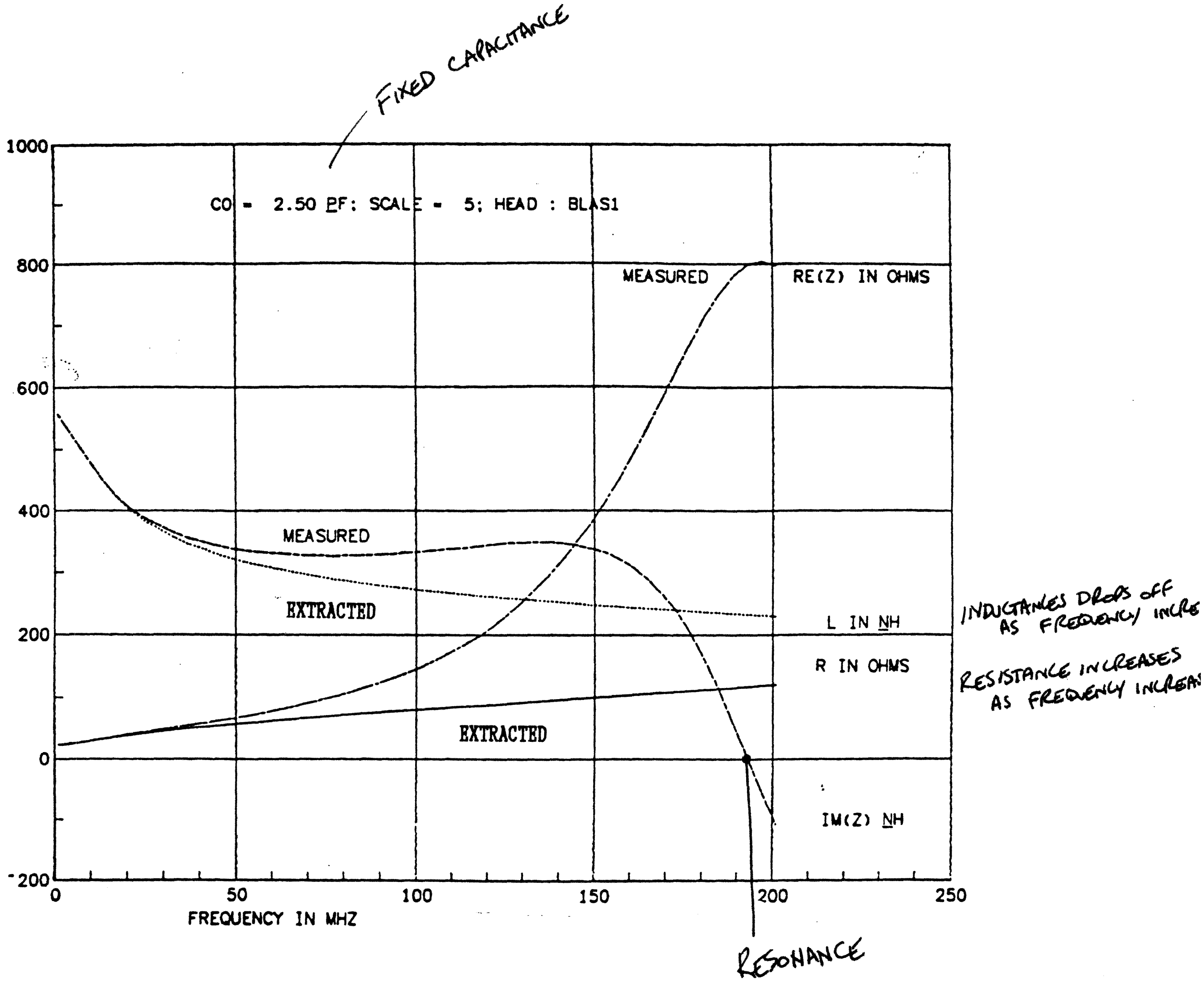
RELATIVE PERM

$$L = \mu_o \frac{N^2 A_{COIL}}{\ell_{\substack{COIL \\ PATH}}} (\mu' - \mu''j) = \cancel{\mu_o \mu' \frac{N^2 A_{COIL}}{\ell_{COIL}}} = L_o\left(1 - j\frac{\mu''}{\mu'}\right) \Big] \; ?$$

Lo is low frequency INDUCTANCE value and decrease as frequency increases.

R increases as frequency increases.

$$L_o = \mu_o \mu' \frac{N^2 A_{COIL}}{\ell_{\substack{COIL \\ PATH}}}$$



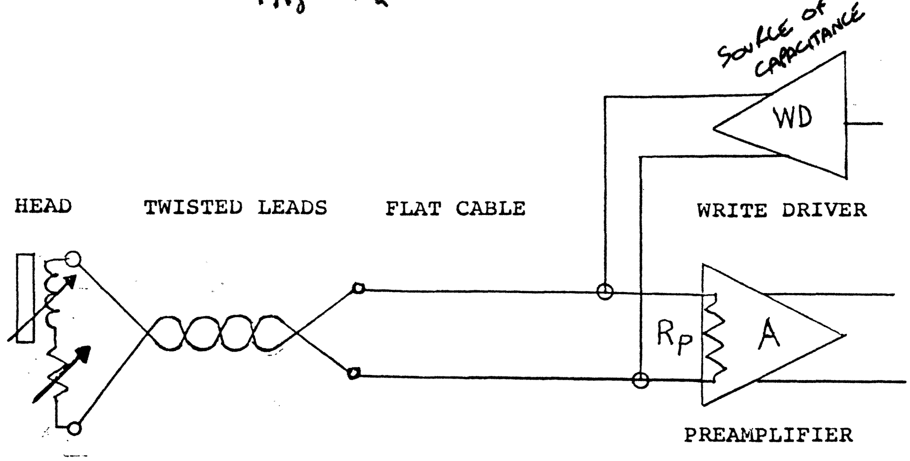
The measured real and imaginary parts of Z of an inductive head.

The L and R are calcualted from Re(Z) and Im(Z).

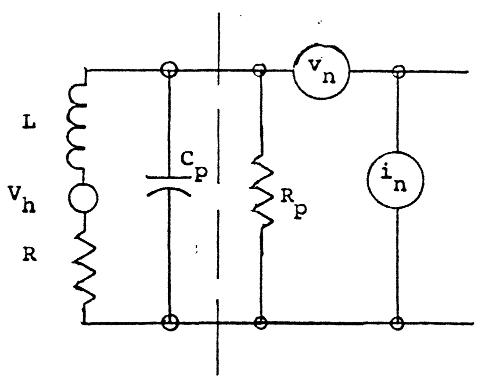
9.6 AMPLIFIER NOISE

Head and amplifier noise have to be considered together.

Arm Electronics $\sqrt{N_d^2 + N_a^2}$



Simple Equivalent circuit

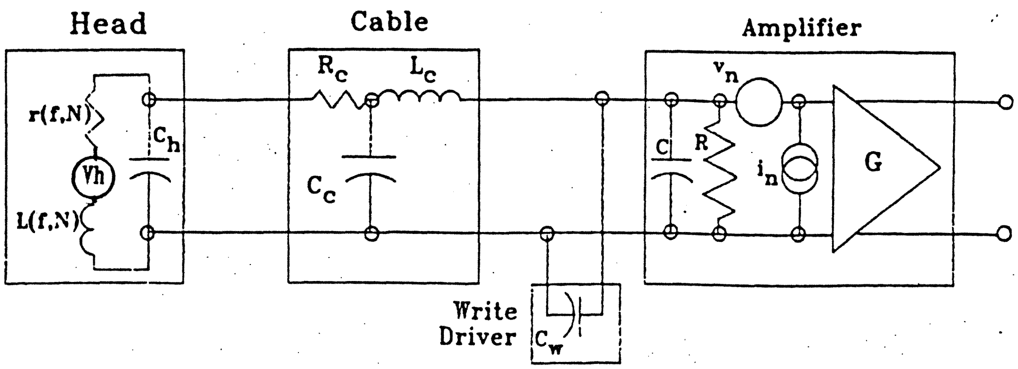


v_n is the voltage equivalent noise source of the amplifier and is measure at the amplifier output, with the input shorted, as $A \cdot v_n$ where A is the gain of the amplifier.

i_n is the current equivalent noise source of the amplifier and is measured at the output of the amplifier, with the input open but well shielded, as $A \cdot |Z_{in}| \cdot i_n$ where $|Z_{in}|$ is the magnitude of the input impedance of the amplifier.

i_n usually low
doesn't contribute much

Complete head/amplifier noise equivalent circuit.



Electronic Noise

Head Noise (Johnson)

$v_{hn} = \sqrt{4kTB\,\Re eZ}$

Amplifier Noise

1) **Voltage Equivalent Noise**

$v_{vn} = v_n\sqrt{B}$

2) **Current Equivalent Noise**

$v_{in} = i_n|Z|\sqrt{B}$

Typical Values

$v_n/i_n = 180\ \Omega$

$R = 1\ k\Omega$

$C = 15\ pF$

$L_c = 40\ nH$

$R_c = 1\ \Omega$

$C_c = 4\ pF$

$r(1\ MHz, 31) = 24\ \Omega$

$L(1\ MHz, 31) = 500\ nH$

$C_h = 1\ pF$

$C_w = 5\ pF$

Current equivalent noise is proportional to the magnitude of the parallel impedances at the input. The lowest impedance is generally the head impedance.

Thus head resistance contributes to two noise sources, the head Johnson noise and the amplifier noise.

Generally i_n is small and only contributes at high data rates and/or high head resistance values or as the frequency approaches resonance.

$$Na = \sqrt{v_n^2 + i_n^2 \cdot |Z|^2} \cdot \sqrt{B} \qquad (9.3)$$

Values for the 3380 amplifier are:

$v_n \approx 1\ nV/\sqrt{Hz}$

$i_n \approx .02\ nA/\sqrt{Hz}$

9.7 HEAD SNR AS FUNCTION OF NUMBER OF TURNS

Since the head output voltage is proportional to the number of turns, the obvious way to increase output is to increase the number of turns, N, -- **BUT** -- there is a point of diminishing returns.

First of all, as N increses the resonant frequency decrease which increases the head impedance and the noise due to the amplifier current equivalent noise source.

At best SNR $\alpha \sqrt{N}$ since signal and resistance both increase with N and noise $\alpha \sqrt{R}$.

If the additional turns are longer than earlier turns the resistance will go up faster than the signal.

In a thin film head the windings must at some point become smaller in cross section due to space constraints leading to a larger than linear increase in R with N.

In a film head with a fixed coil area R actually goes up faster than N^2 and the SNR of head actually goes down as N increases.

$$R \; \alpha \; \frac{1}{h \cdot w}$$

In the best case

$$1 \; \alpha \; N$$

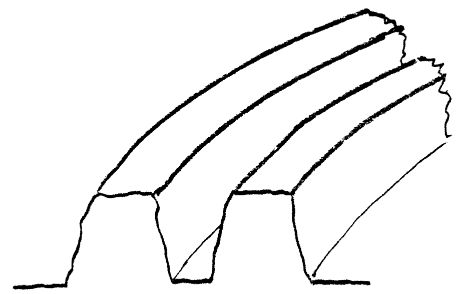
$$\frac{1}{w} \; \alpha \; N$$

$R \; \alpha \; N^2$ and SNR would be constant.

As the winding width decreases the space between winding stays constant limited by the characteristics of the photoresist and etching and process. Thus

$\frac{1}{W} \alpha N^{>1}$ and

$R \alpha N^{>2}$

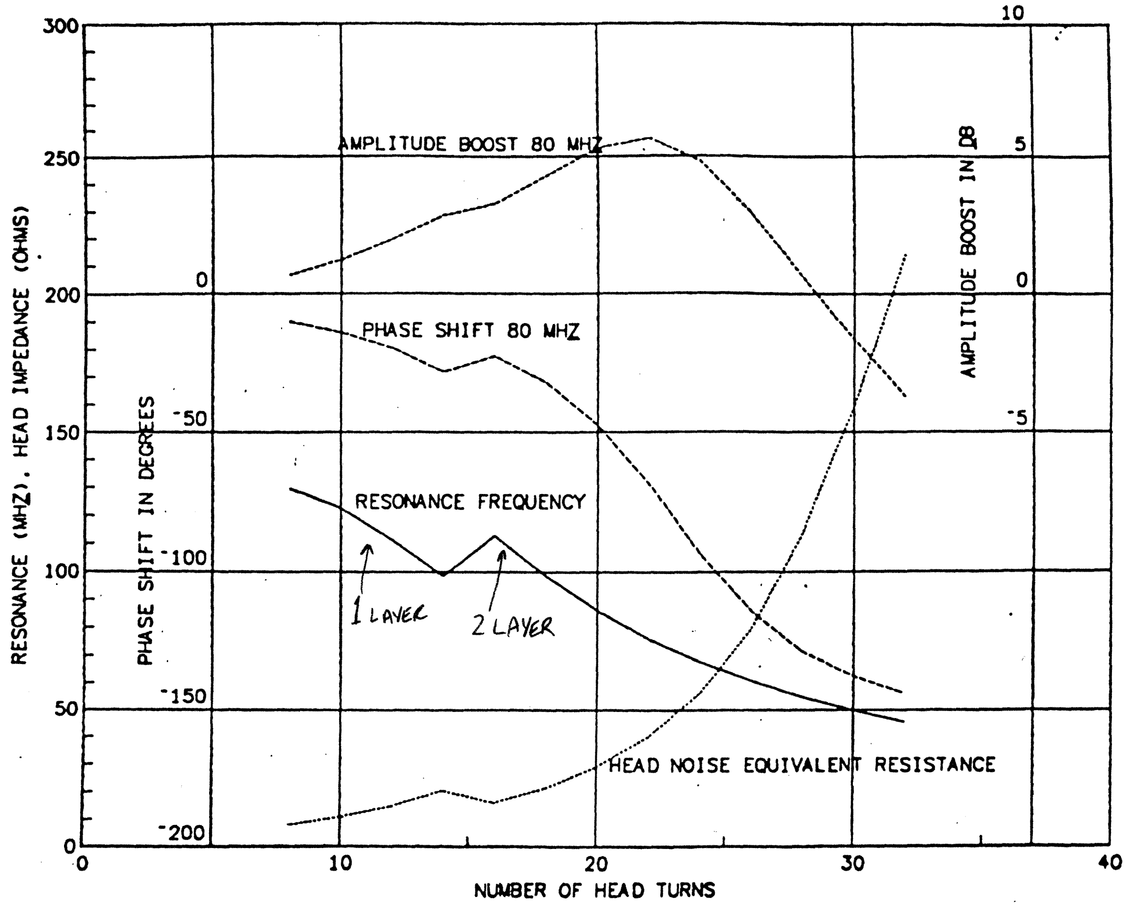


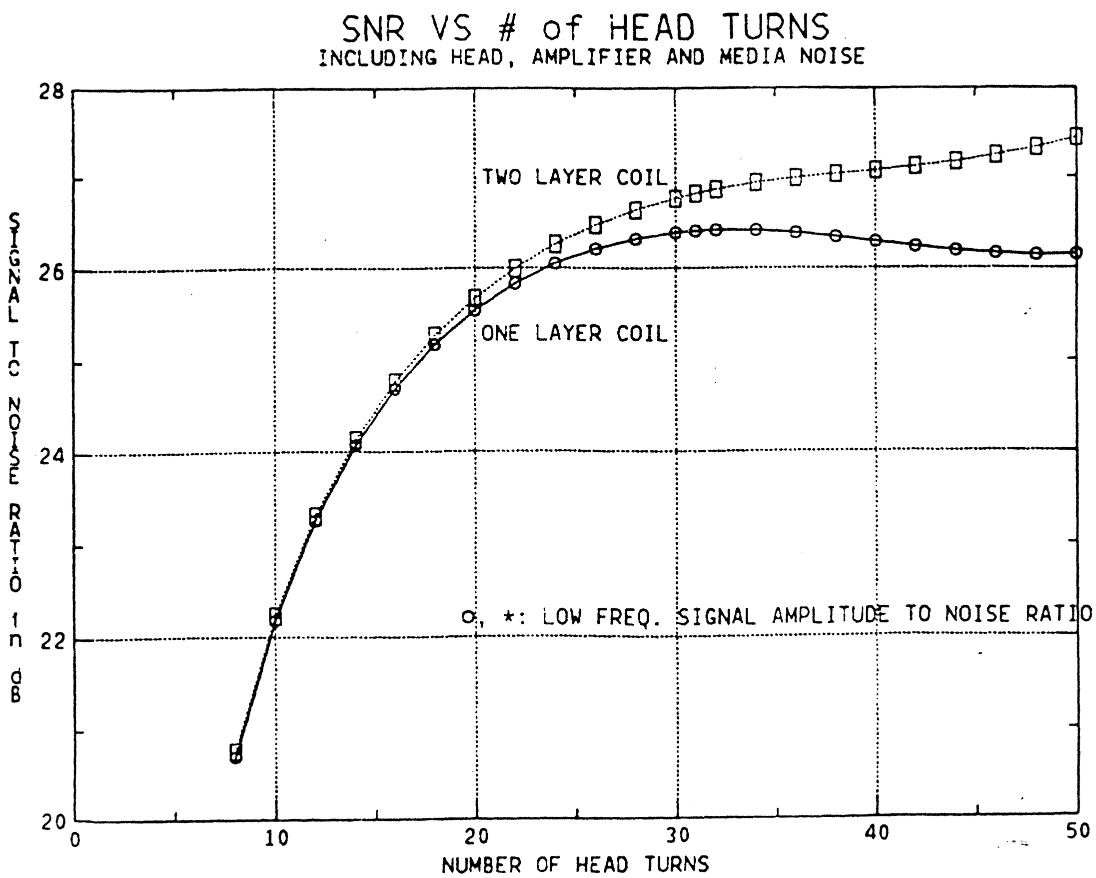
Once the head noise becomes dominant there is no futher increase in over all SNR with increasing N.

Going to a second or third coil layer increases the area and the amount of copper in the winding and decreases the noise for a given N.

The first figure of page ~~13~~ 11 shows how noise resistance, resonant frequency phase shift and amplitude vary with the number of head turns.

The jumps in the resonance and phase show the effect of going from a one to two layer winding.


AMPLITUDE BOOST 80 MHZ
PHASE SHIFT 80 MHZ
RESONANCE FREQUENCY
1 LAYER
2 LAYER
HEAD NOISE EQUIVALENT RESISTANCE
RESONANCE (MHZ), HEAD IMPEDANCE (OHMS)
PHASE SHIFT IN DEGREES
AMPLITUDE BOOST IN DB
NUMBER OF HEAD TURNS


SNR VS # of HEAD TURNS
INCLUDING HEAD, AMPLIFIER AND MEDIA NOISE
TWO LAYER COIL
ONE LAYER COIL
o, *: LOW FREQ. SIGNAL AMPLITUDE TO NOISE RATIO
SIGNAL TO NOISE RATIO in dB
NUMBER OF HEAD TURNS

9.8 DISK NOISE

NO MEDIUM IS MAGNETICALLY HOMOGENOUS
PARTICULATE- NOISE BY PARTICLE DISTRIBUTION
FILM- GRAIN STRUCTURE

Whereas Johnson noise is independent of the voltage or signal across the source resistance, disk noise is proportional to the siganl derived from the disk.

This is because disk noise is the variation in signal due to inhomogeneity in the medium material i.e. variations in the siganl due to macro variations in the magnetization or in the transition. -- No siganl, no noise.

Disk noise has a Gaussian distribution and is measured and expressed as rms.

If two adjacent widths are added the siganls will add and increase proportional to the sum of the width while the noise will add rms and increase as the square root of the width.

Thus disk noise is α $\sqrt{W}$ and signal is α to W and

$N_d \approx \frac{1}{\sqrt{W}}$

Disk SNR is α $\sqrt{W}$.

$S \approx \frac{1}{W}$

$SNR \approx \frac{N}{N_d} \approx \frac{\frac{1}{W}}{\frac{1}{\sqrt{W}}} \approx \frac{1}{\sqrt{W}}$

The noise mechanism in particulate and film disks is different.

PARTICULATE DISKS

$SNR \sim \underset{\text{IMPEDANCE}}{Z} \sim$ HEAD SIZE (SCALE)

$Z \sim \sqrt{N}$

Noise is amplitude variations due to macro variations of moment. Sources are:

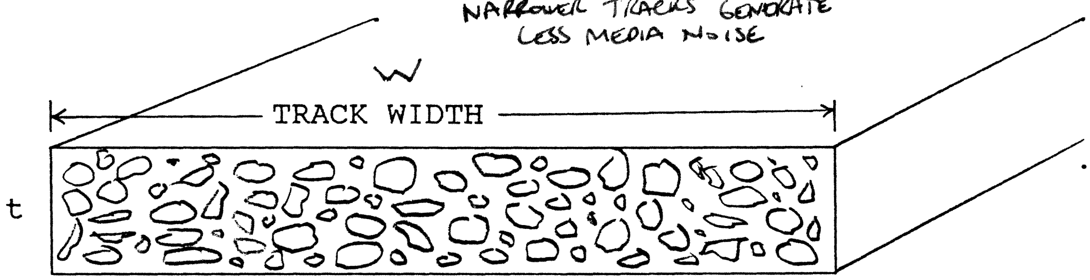
particle size and shape variations

nonuniform dispersion

presence of alumina

FERRITE HEADS
INDUCTANCE $\approx 10^{-6}$ H
RESISTANCE $\approx 10\ \Omega$

NARROWER TRACKS GENERATE LESS MEDIA NOISE



Characteristics of particulate disk noise:

Signal and noise are both proportional to moment and thickness.

Noise decrease as size of particle decrease for same moment. i.e. smaller particle yields better disk SNR.

Spacing loss has same effect on signal and noise.

Velocity has the same effect on signal and noise.

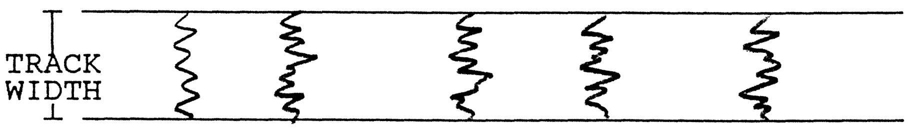
Signal adds coherently, noise adds incoherently.

Noise decrease slightly as data density increases with same head.

FILM HEADS
INDUCTANCE IS NEGLI. $<10^{-8}$ H
RESISTANCE 10-20Ω

METAL FILM DISK

The best model relates to transition jitter.



The transitions tend to follow grain boundries.

The mean position of the transitions varies in a random manner.

This random, position variation can be equated to transitions with no position variation plus noise.

There are a variety of film materials with some differences in characteristics.

Noise is affected by texture of substrate and undercoats that affect grain growth of the magnetic material.

If the grains can be made smaller the noise is lower but also there is more macro vaiation in Hc and S* is lower.

Many of the properties of noise from film disks are the same as the noise from particulate disks. Namely:

Signal and noise both proportional to moment and thickness.

Velocity has the same effect on signal and noise.

Signal adds coherently, noise adds incoherently.

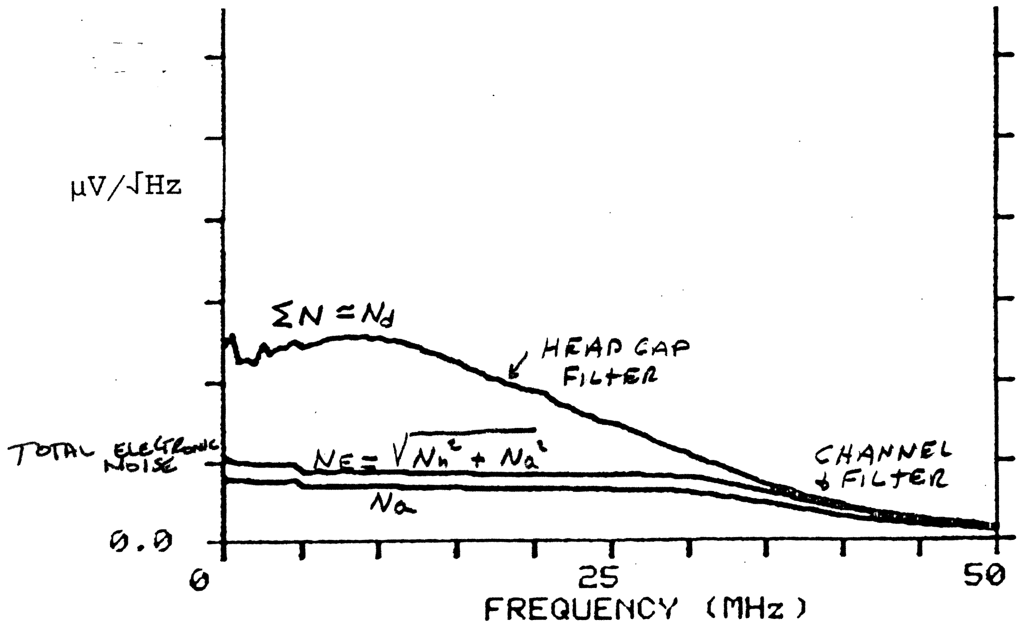
SNR increases slightly with closer HEAD/MEDIA spacing.

The major difference is that film disk noise increases as data density increases.

BUY S/N WITH LOSS IN RESOLUTION

CHROME UNDERCOAT

9.9 MEASURED NOISE VS FREQUENCY



NOISE CURVE

Na, amplifier noise, is here measured with the head unloaded (not on the disk) and the input shorted. this assumes that the voltage equivalent noise is dominant.

Ne, the total electronic noise, is then measured with the head unloaded and connected to the amplifier.

ΣN, the total noise, is measured with the head loaded on the spinning disk.

The noise value in µv in each case is the integral under the appropriate curve. Thus the units of the ordinent is µV/√Hz.

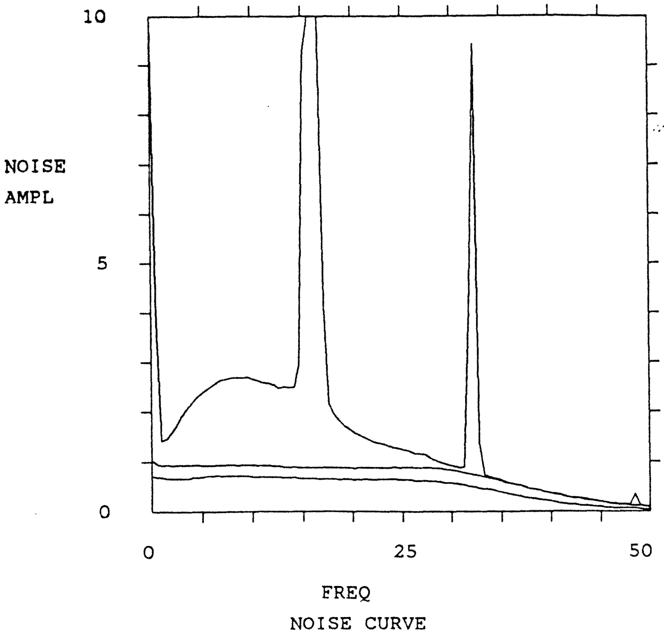
In principle the noises can be separated by using the total noise equation (9.1).

AS IS SEEN ABOVE:

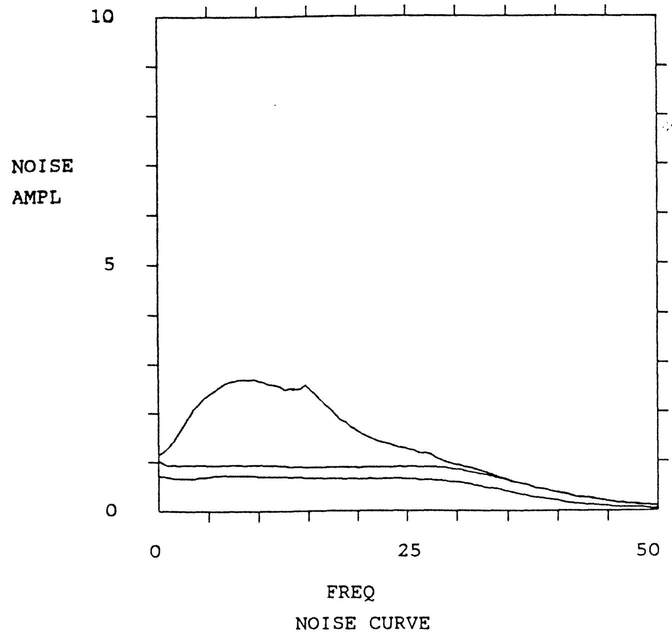
Disk noise is limited frequency-wise by the gap and spacing losses of the head. AND NOT CHANNEL BANDWIDTH

Amplifier and head noise (which are α √B, the channel bandwidth) are limited by the electronics low pass filter.

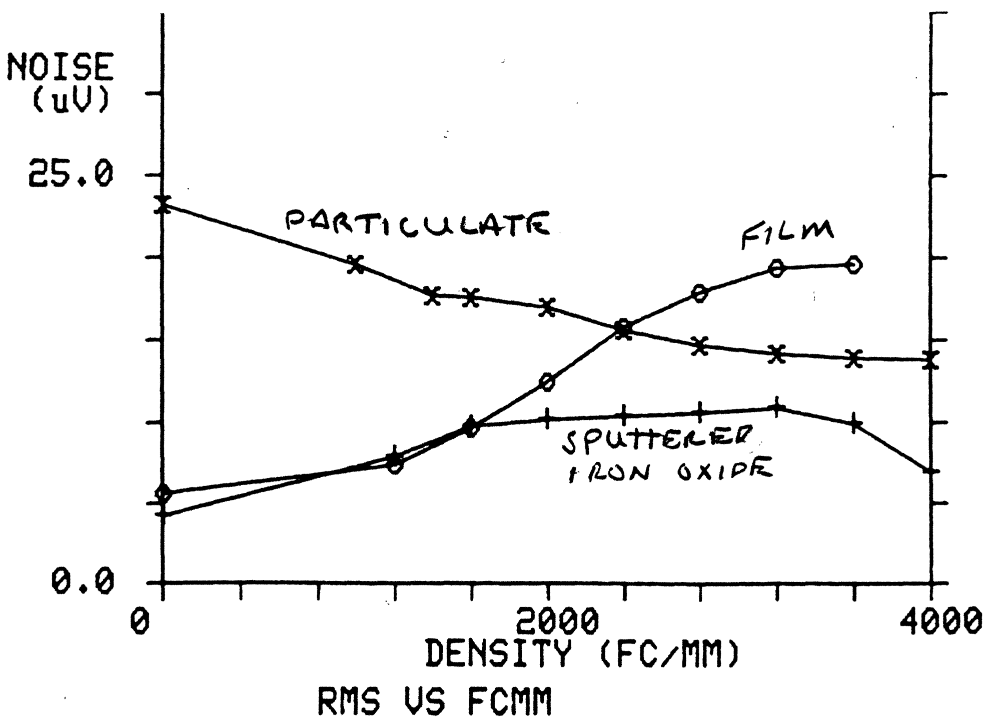
9.9 FILM DISK NOISE A FUNCTION OF DATA FREQUENCY

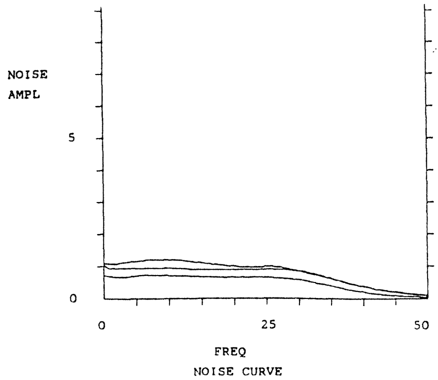


AFTER DISK WRITE @ 16.0 MHZ

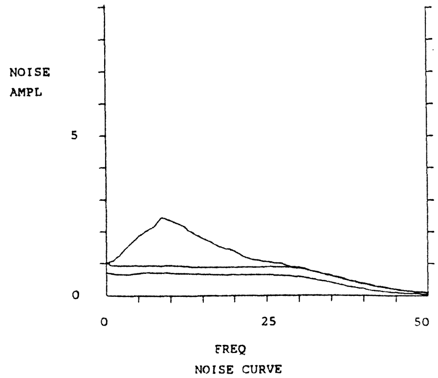


AFTER DISK WRITE @ 16.0 MHZ

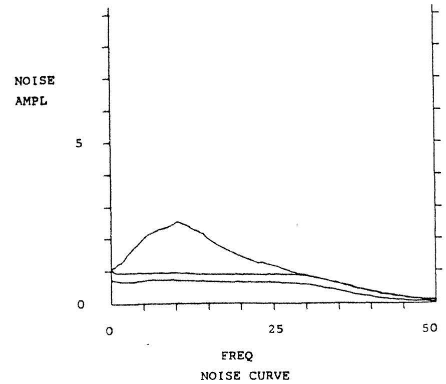




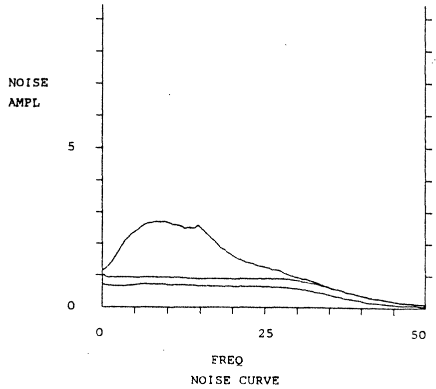
AFTER HEAD DC ERASE OF DISK



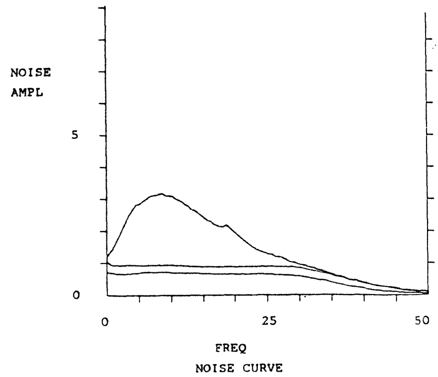
AFTER DISK WRITE @ 10.0 MHZ



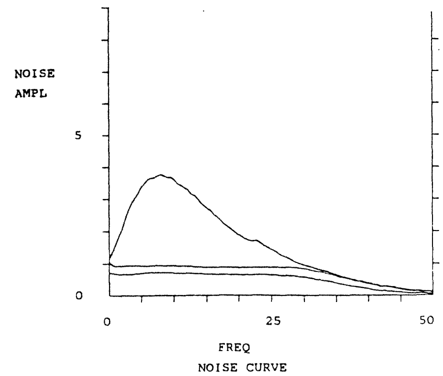
AFTER DISK WRITE @ 12.0 MHZ



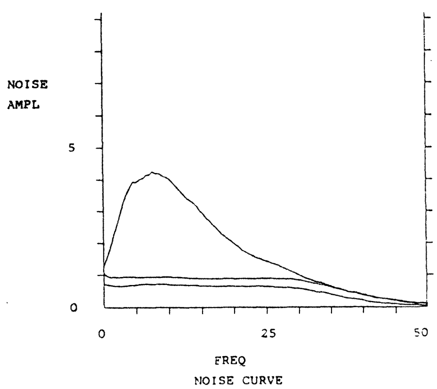
AFTER DISK WRITE @ 20.0 MHZ



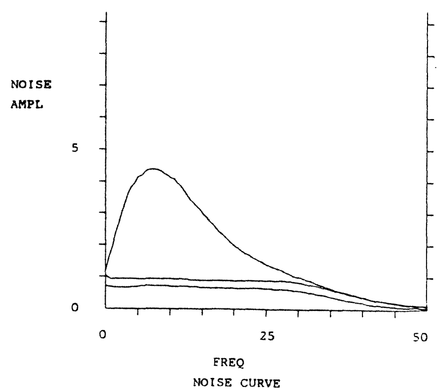
AFTER DISK WRITE @ 24.1 MHZ



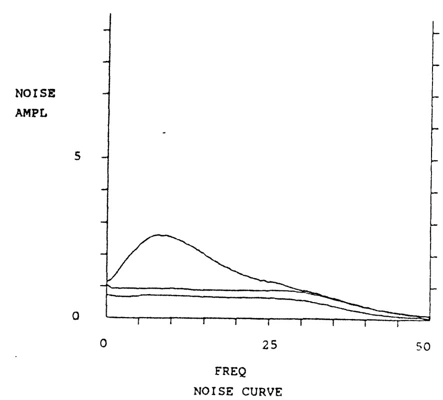
AFTER DISK WRITE @ 28.1 MHZ



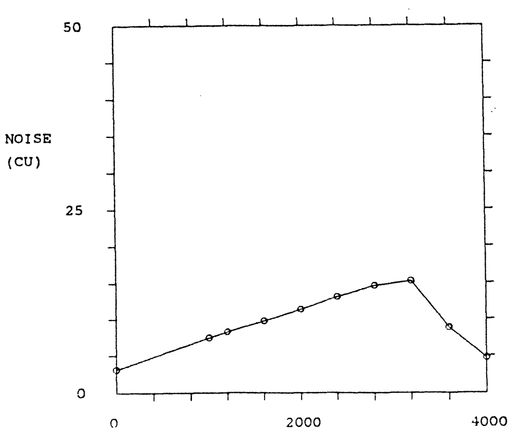
AFTER DISK WRITE @ 32.1 MHZ

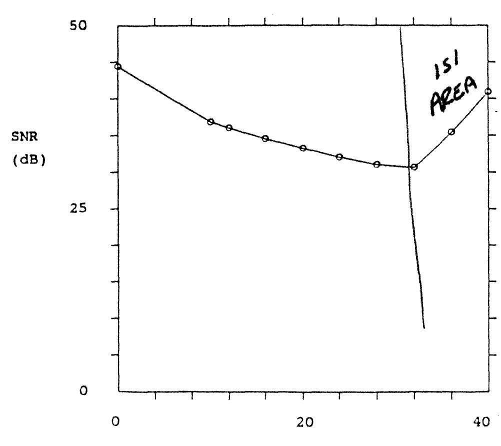


AFTER DISK WRITE @ 36.1 MHZ



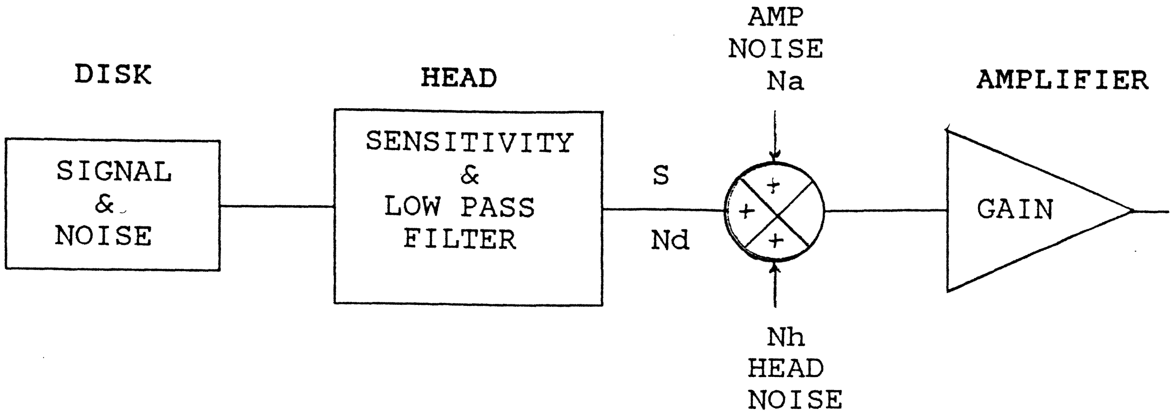
AFTER DISK WRITE @ 40.1 MHZ





9.10 THE MAGNETIC CHANNEL SNR

Now going back to the channel noise diagram of section 9.3.



$$SNR = \frac{\text{Signal}}{\sqrt{Nd^2 + Nh^2 + Na^2}} = \frac{V_{b\text{-}p}/\sqrt{2}}{\sqrt{\Sigma\,\text{NOISE}^2}} \qquad (9.2)$$

NOISE USUALLY IN RMS

The characteristics of the head have the same effect on disk signal and disk noise.

This can be seen by writing equation (9.2) in terms of the pulse sensitivity, Ps, of section 7.2.

$$SNR = \frac{Ps \cdot W/\sqrt{2}}{\sqrt{Nd^2 + Nh^2 + Na^2}} \qquad Ps = \frac{V_{b\text{-}p}/\sqrt{2}}{W} \qquad (9.4)$$

As discussed in section 9.9, disk noise is proportional to the $\sqrt{W}$ and will be proportional to Ps. (9.4) can be written as

$$SNR = \frac{Ps \cdot W/\sqrt{2}}{\sqrt{(Nd' \cdot \sqrt{W} \cdot Ps)^2 + Nh^2 + Na^2}} \qquad (9.5)$$

UMN Where Nd′ is defind as the unit media noise and is the disk noise/$\sqrt{}$(unit W)/(unit Ps). Thus

$$Nd = Nd' \cdot Ps \cdot \sqrt{W} \qquad (9.6)$$

Dividing numerator and denominator by Ps yields

$$\mathrm{SNR} = \frac{W}{\sqrt{(Nd')^2 W + (Nh^2 + Na^2)/Ps}} \qquad (9.7)$$

DISK HEAD & AMP

The significance is that as Ps increases, the effect of the head and amplifier noises decrease and in the limit the SNR becomes the SNR of the disk.

$$\lim_{Ps \to \infty} \mathrm{SNR} = \frac{\sqrt{W}}{Nd'}$$

Thus, even if Ps can be increased with no bad side effects, the benefit is limited.

The SNR requirements for a 2,7 code peak detection channel is in the range of 26 - 27 dB base-peak/rms.

1,7 25-26 dB

9.12 SNR AND ERROR RATE

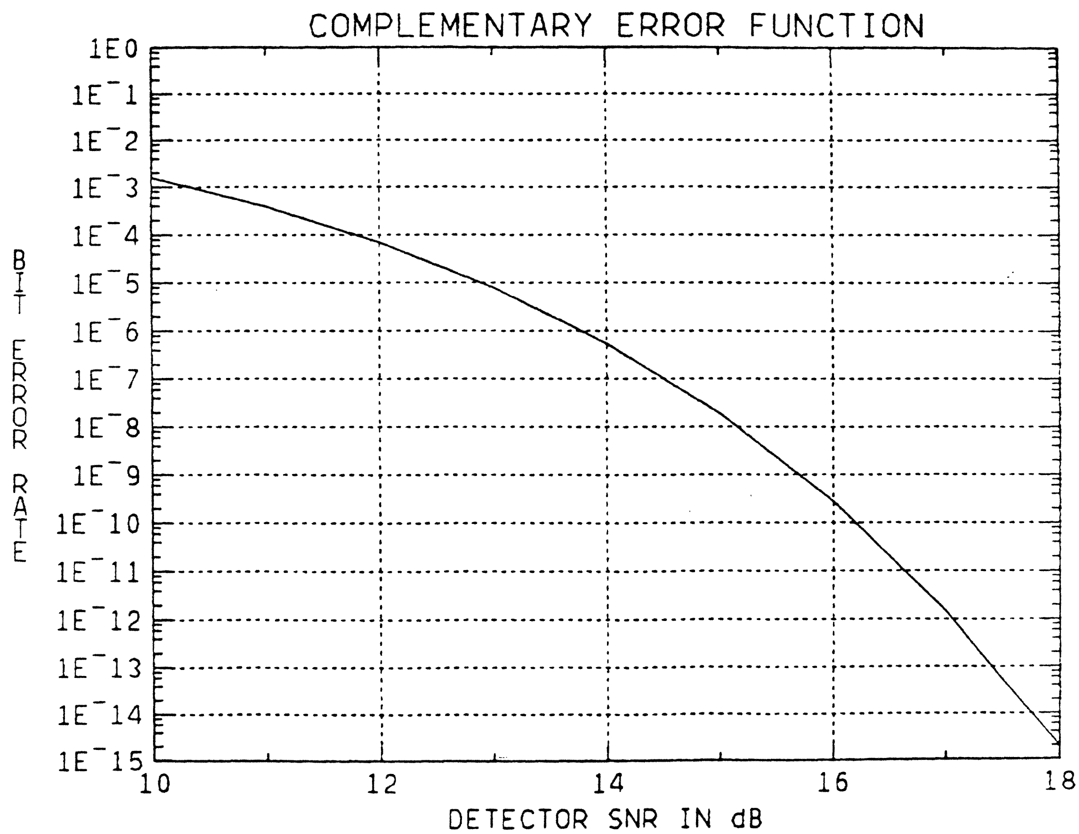
The projected error rate is related to SNR via the complemtary error function.

$$ER = CEF(SNR/\sqrt{2}) \quad \text{SNR not in dB.}$$

Thr SNR is the SNR at the detector not at the amplifier.

There is a loss in the electronic channel and in the detector. (detection loss factor). For a 2,7 code peak detection channel at 85% resolution this loss is about 11.4 db.

desired on track error rate is in the E-7 to E-9 range depending on the application.



SNR
− 11.4 dB
DETECTER SNR

NOISE PROBLEMS

PROBLEM 9.1

A head disk combination has a resolution of 70% at the all ones frequency. What is the dB difference in the SNR definitions of page 9.2.

PROBLEM 9.2

a. Derive the equation for unit media noise (UMN) as a function pulse sensitivity Ps and track width W. 9.17

b. The SNR for a disk type is advertized as 33 dB for W = 10 μ. What is the UMN?

c. You want to use this disk in a product with W = 6μ. You measure Vp-p as 700 μV. What is the disk noise and disk SNR under these condition?

PROBLEM 9.3

The noise of an amplifier is measured with the input shorted and found to have a noise voltage of 6 μV rms with a 30 MHz bandwidth. The noise of a head and this amplifier to gether is found to be 8.5 μV rms at 30 MHz.

What is the head noise for a bandwidth of 20 MHz?

PROBLEM 9.4

A given disk is stated to have a SNR of 30 dB when measured at 40 MHz with the head and amplifier of problem 3 with Tw = 10 μ.

a. If the low frequency peak to peak signal is 600 μV, what is the disk noise in μV? $30\,dB = 20\,Log\left(\frac{S_{RMS}}{N_{RMS}}\right) = 20\,Log\left(\frac{600/\sqrt{2}}{N_{RMS}}\right)$

b. What is the total SNR if you use this disk with a similar head with Tw = 8μ and at a bandwidth of 30MHz?

$$SNR = \frac{V_{b-p}/\sqrt{2}\left(\frac{\sqrt{8}}{\sqrt{10}}\right)}{\sqrt{\left(N_d \frac{\sqrt{30}}{\sqrt{40}}\right)^2 + N_h^2 + N_a^2}}$$

PROBLEM 9.5

When measured on a test stand at 40 MHz a disk has a noise of 8.5 μV rms and the head and amplifier have a combined noise of 10 μV and the Vp-p is 500 μV.

a. What is the dB SNR of the combination if u~~n~~sed in a channel with a BW of 27 MHz.

b. What is the approximate on track error rate (OTER) with a 2,7 code peak detection channel?

PROBLEM 9.6

a. If the data rate for the components of problem 9.5 were to be incresed requiring a BW of 40 MHz, what would be the loss in SNR and the new OTER.

b. In addition the higher data rate it is desired to increase track density requiring W = 8.5 μ. What is the loss in SNR due to both changes and what is the projected new OTER.

c. What would you recommend about making these changes?

11 EQUALIZATION - DECREASE SNR BOOST ADDS NOISE

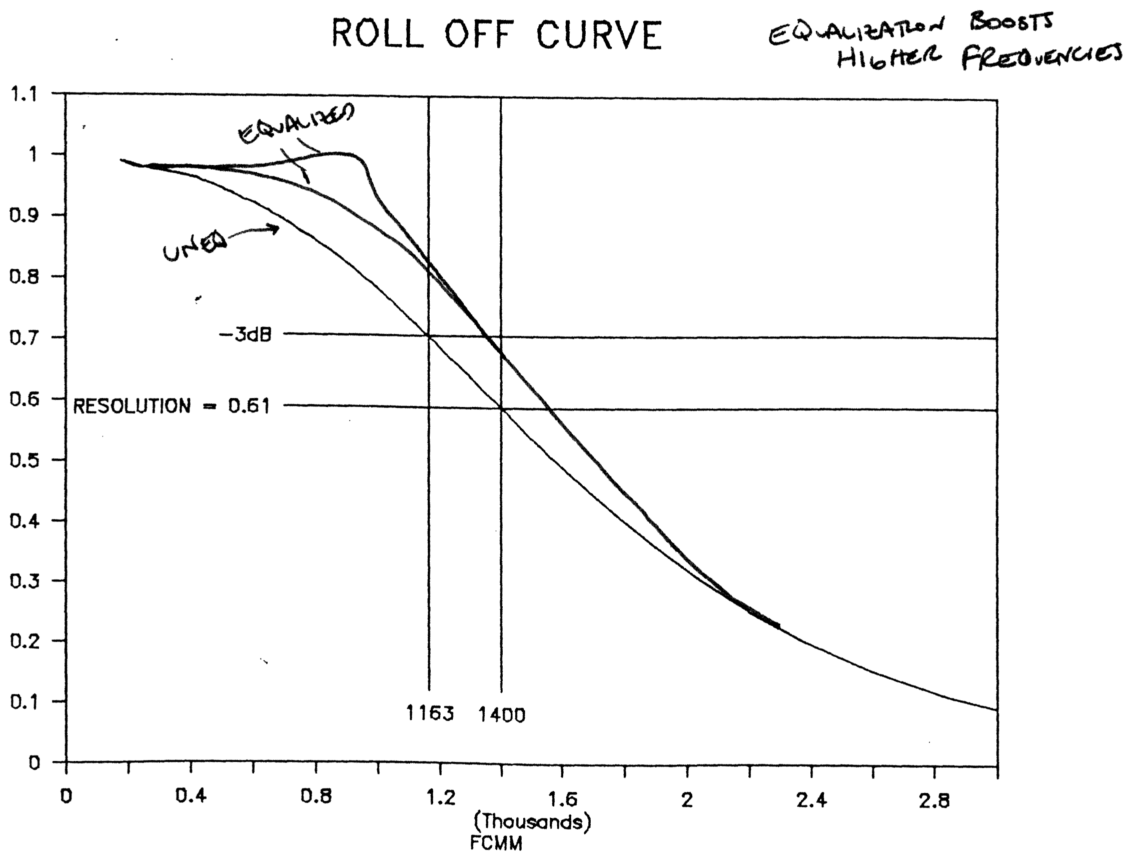
11.1 INTERSYMBOL INTERFERENCE

As the spacing between transitions decreases there is partial cancelation resulting in loss in amplitude and a shift of the readback pulse peak.

Amplitude vs density yields a roll-off curve. The -3dB density or the resolution at some specific density characterizes the components. Different detection channels have different resolution requirements for satisfactory error rate.

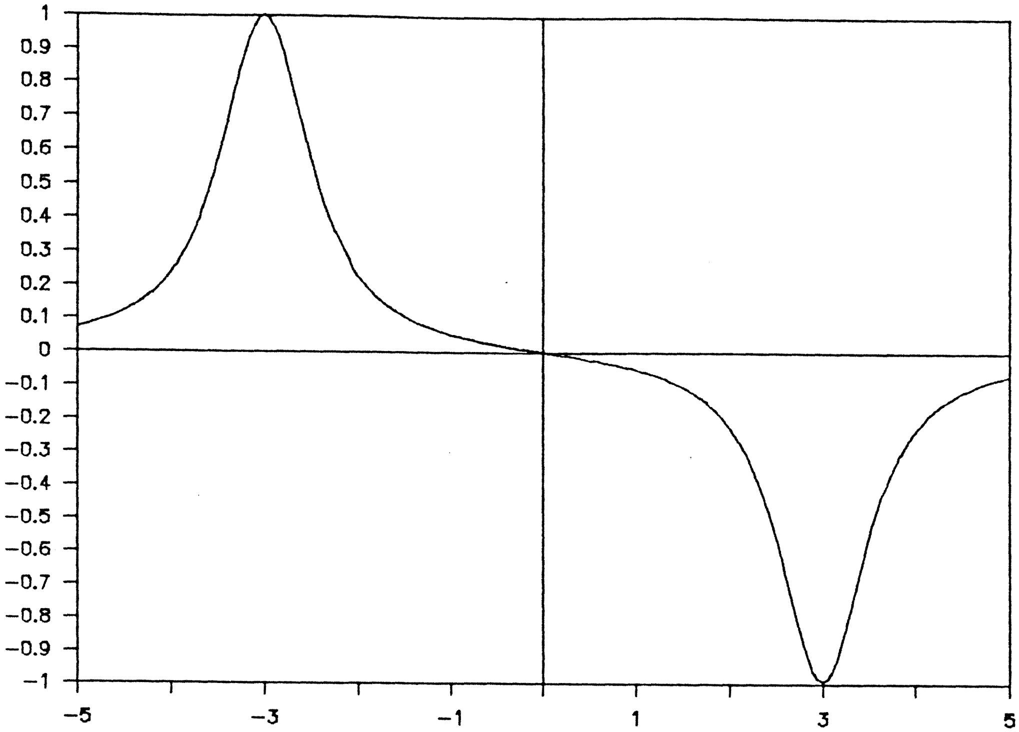
The process is linear up to fairly high densities. that is, a pulse train with variable spacing can be constructed by the superposition of isolated pulses.

Reslolution loss and is primarily an inner diameter problem since as the radius increases so does the velocity and the transitions are further apart.



If 1400 fcmm is your design point and .61 resolution is not high enough, equalization may solve the problem.

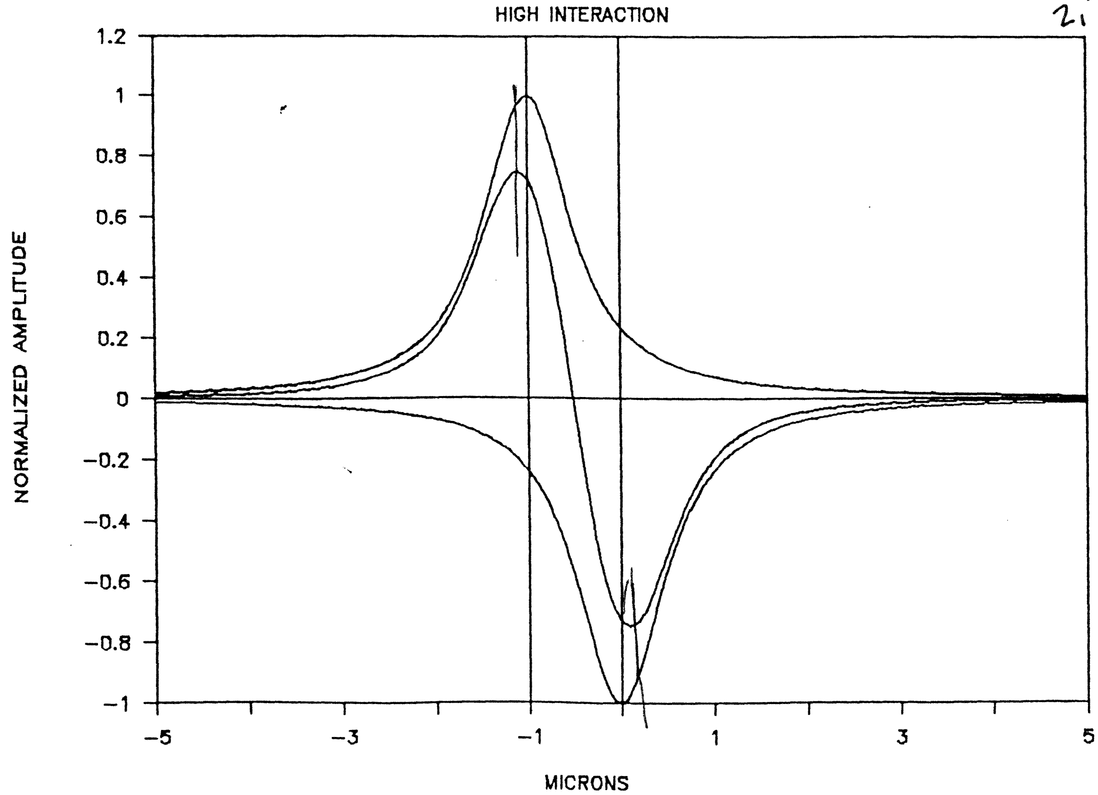
DI-BIT WITH LITTLE INETERACTION

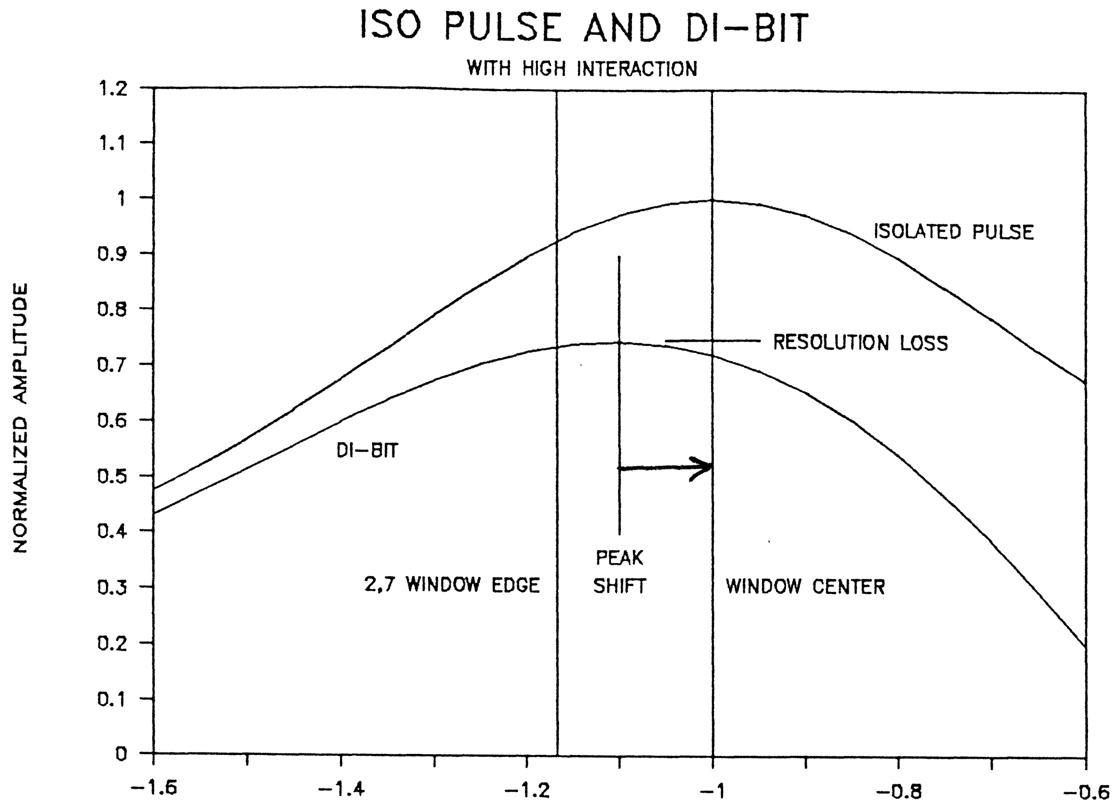


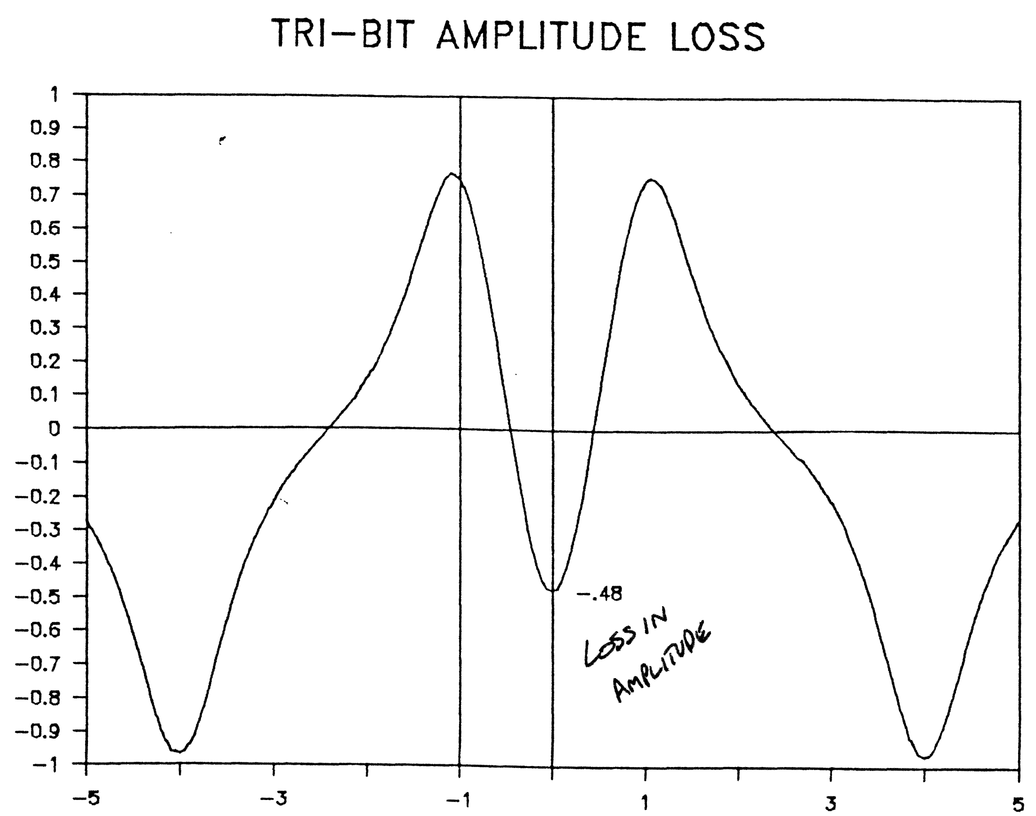
1,7 HAS 30% WIDER WINDOW
2,7 HAS NARROWER WINDOW
DIBIT EXCERSIZES 2,7 BET[illegible]
2,7 HAS 10% MORE BITS / FLUX REV.

ISOLATED PULSES AND DI-BIT

HIGH INTERACTION




ISO PULSE AND DI-BIT
WITH HIGH INTERACTION
NORMALIZED AMPLITUDE
ISOLATED PULSE
RESOLUTION LOSS
DI-BIT
2,7 WINDOW EDGE
PEAK
SHIFT
WINDOW CENTER
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1.6
-1.4
-1.2
-1
-0.8
-0.6


TRI-BIT AMPLITUDE LOSS
-.48
LOSS IN
AMPLITUDE
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-5
-3
-1
1
3
5

11.2 SECOND DERIVATIVE EQUALIZATION

The resolution can be increased with equalization. Equalization basically narrows the isolated pulse and in turn decreases peak shift and amplitude loss by subtracting some form of the pulse from itself.

The second derivative of the isolated pulse has a perfect shape for equalization. The ideal 2nd derivative equalizer transfer function is

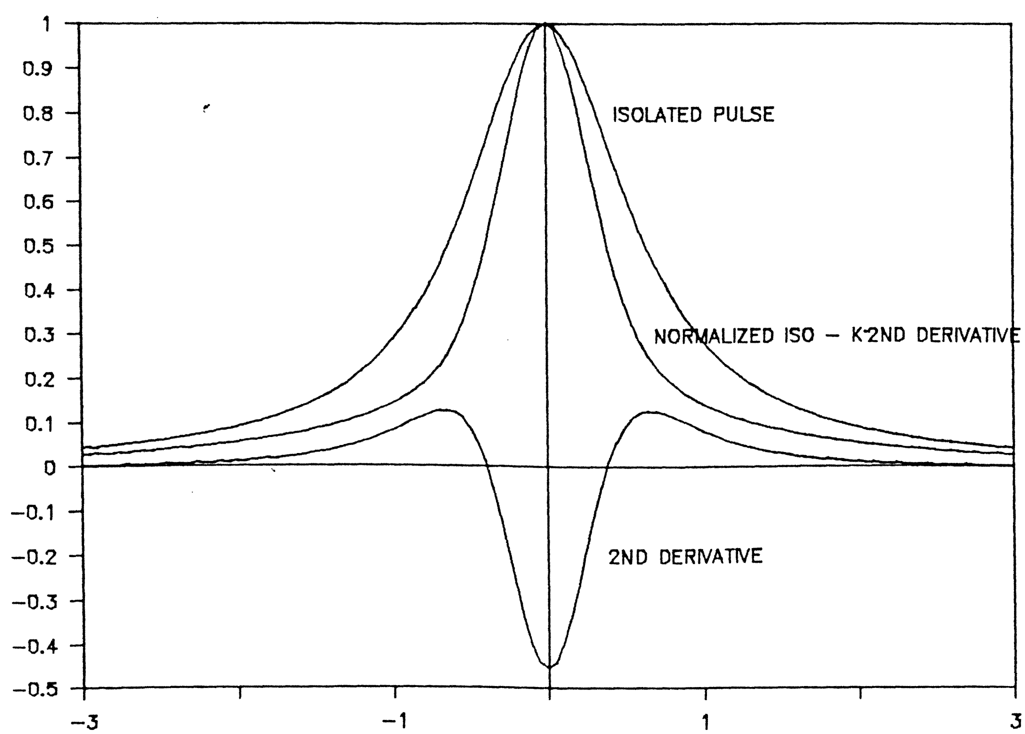
$$1 - KS^2$$

Where k is the amount of 2nd derivative subtracted.

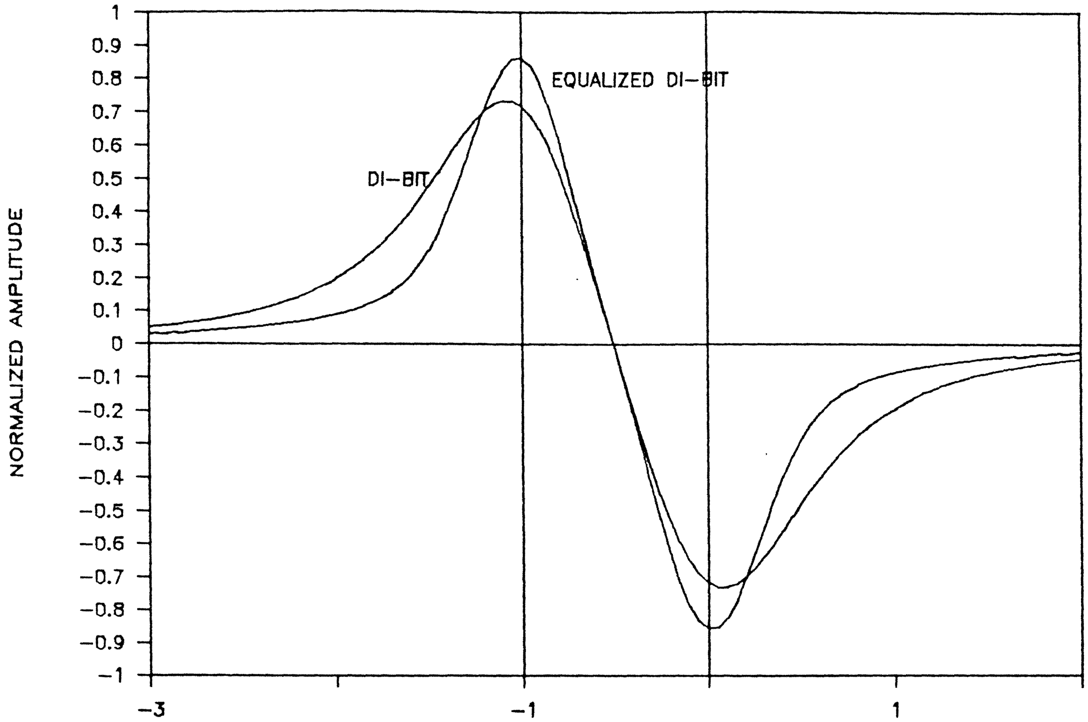
In practice the circuit will also have poles that limit the range of frequency over which diferentiation occures. In a good design the poles will be part of the low pass filiter.

The magnitude of the 2nd derivative increases as the raius increases. Also the need for equalization decreases. K must either decrease with radius or a compromise value be used so as not to over equalize at the mid and outter radii.

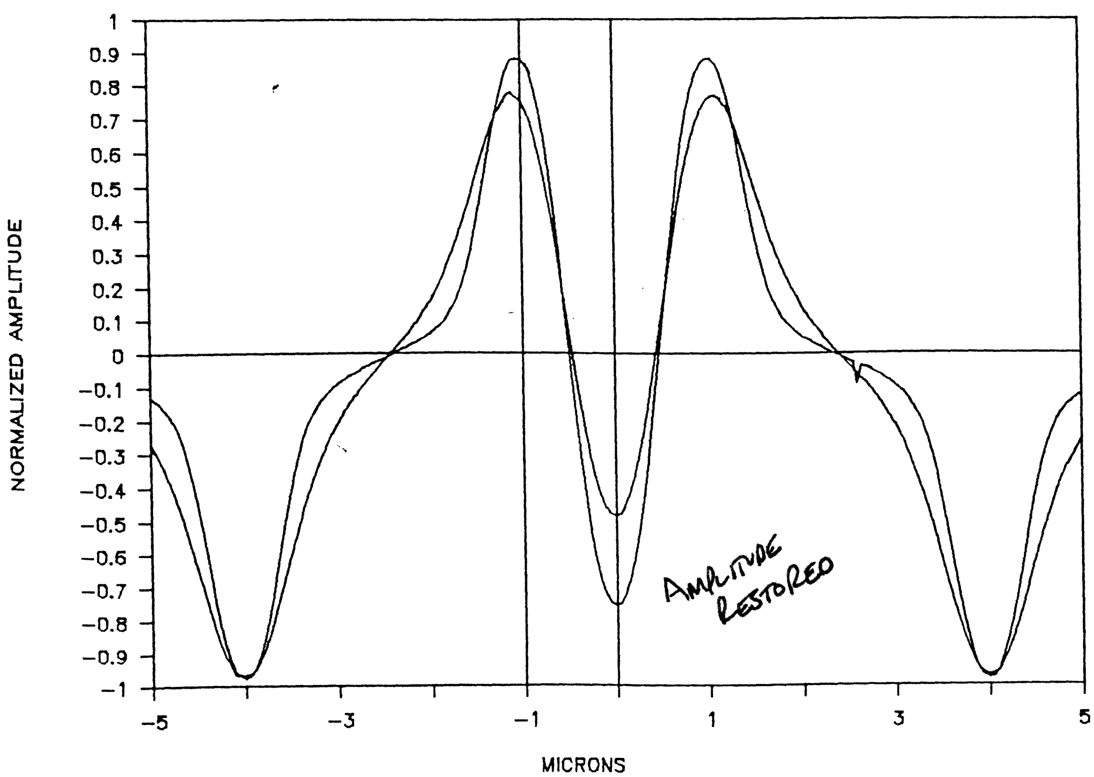
2ND DERIVATIVE EQUALIZATION



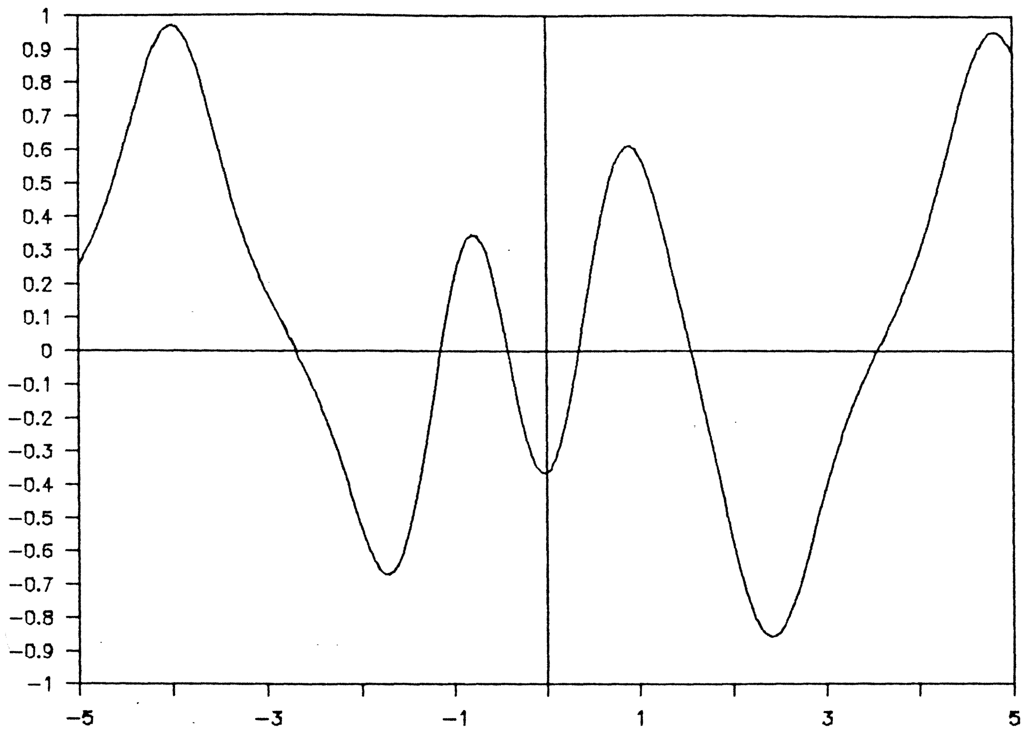
EQUALIZED DI-BIT



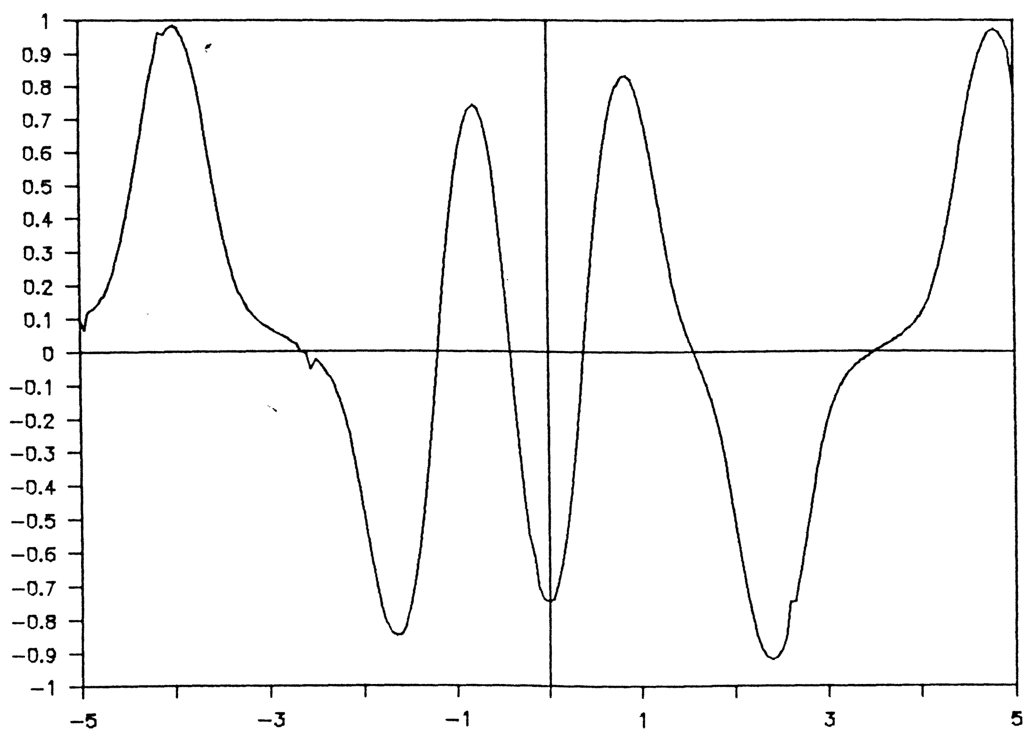
UNEQUALIZED AND EQUALIZED TRI-BIT



UNEQUALIZED PULSE TRAIN

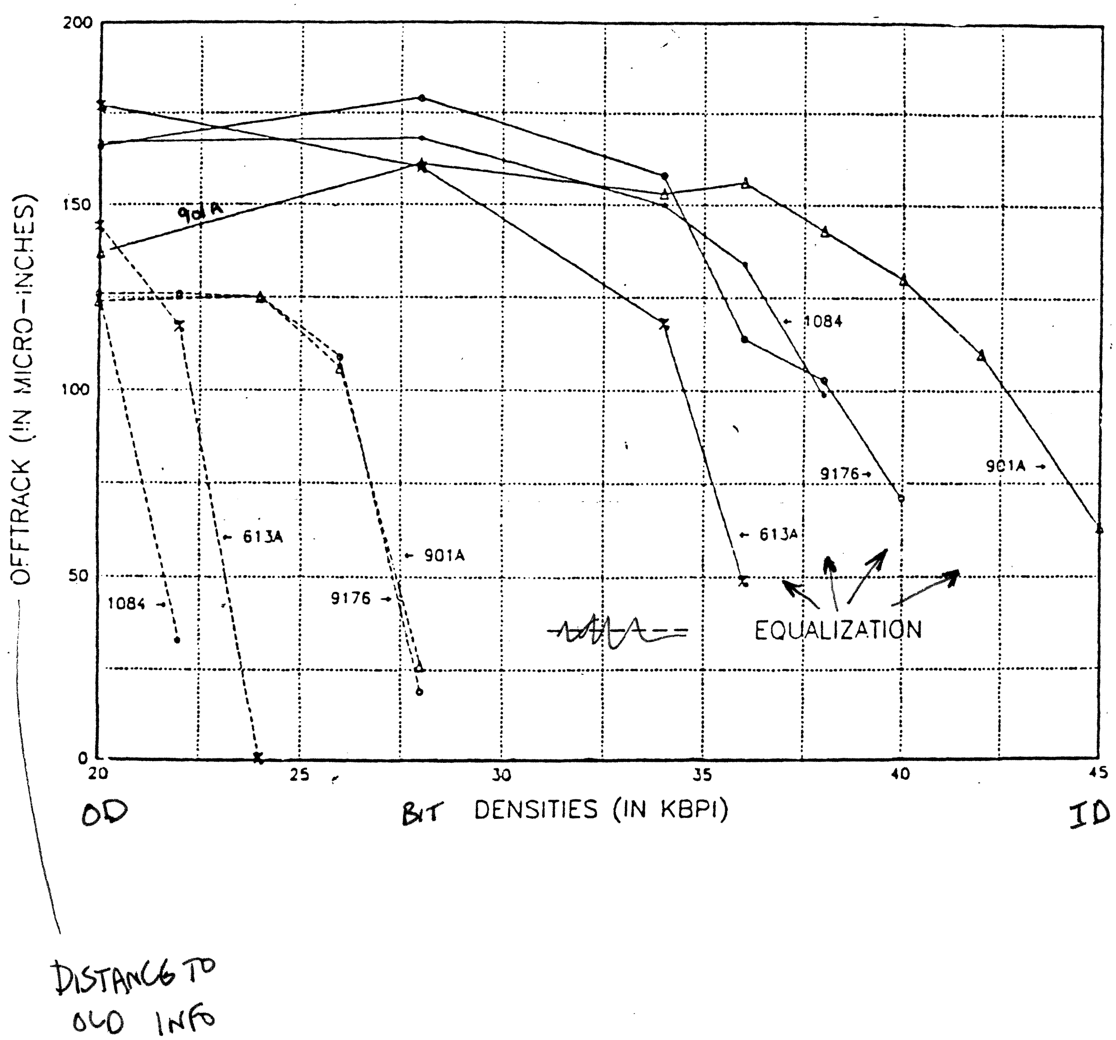


EQUALIZED PULSE TRAIN



11.3 DEMONSTRATION OF LINEAR DENSITY GAINS WITH EQUALIZATION

The linear density gain for 4 different heads is shown with off-track capability vs linear denstiy as a measure of goodness.

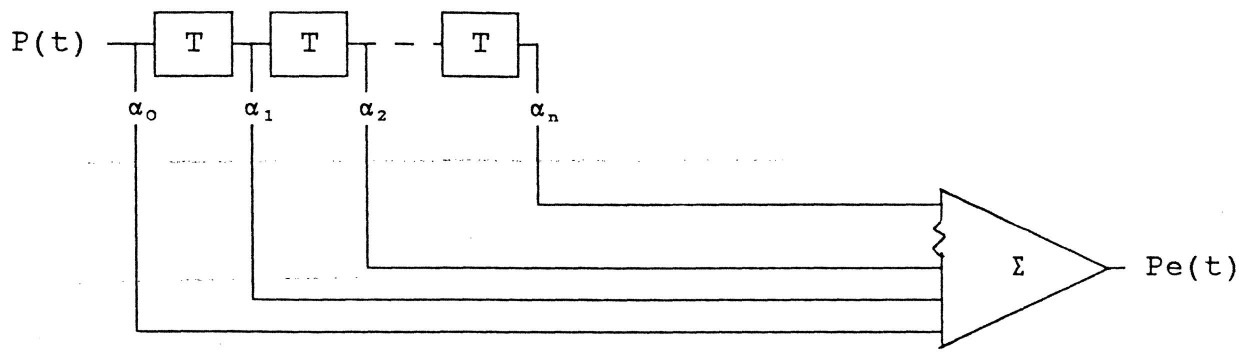


11.3 TAPPED DELAY LINE EQUALIZATION

ANOTHER TYPE

2ND DERIVATE COMPARE PULSE ITSELF

The pulse can be shaped to any degree desired with a tapped delay line.



This form lends itself well design techniques in both time and frequency domain. 10 to 15 tap solutions are not uncommon but it has been considered a laboritory tool and not practical for product implementation.

The 2 tap version is known as the **cosine equalizer.** referenced to the center tap

$$Pe(t) = \alpha_0 P(t) + \alpha_1 P(t-T) + \alpha_2 P(t-2T)$$

In the frequency domain a delay of T is e^{-sT} OR e^{-jvT}

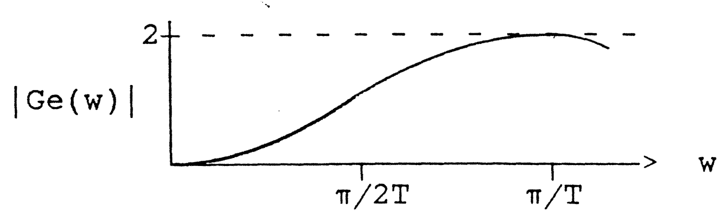
$$Pe(w) = \alpha_0 P(w) + \alpha_1 P(w)e^{-jvT} + \alpha_2 P(w)e^{-jv2T}$$

with $\alpha_1 = 1$ and $\alpha_0 = \alpha_2 = 1/2$

$$Pe(w) = e^{-jvT}[1 - 1/2(e^{jvT} + e^{-jvt})]P(w)$$

$$Pe(w) = [1 - COS(wT)]e^{-jvT}P(w)$$

Ge(w) = EQUALIZER GAIN

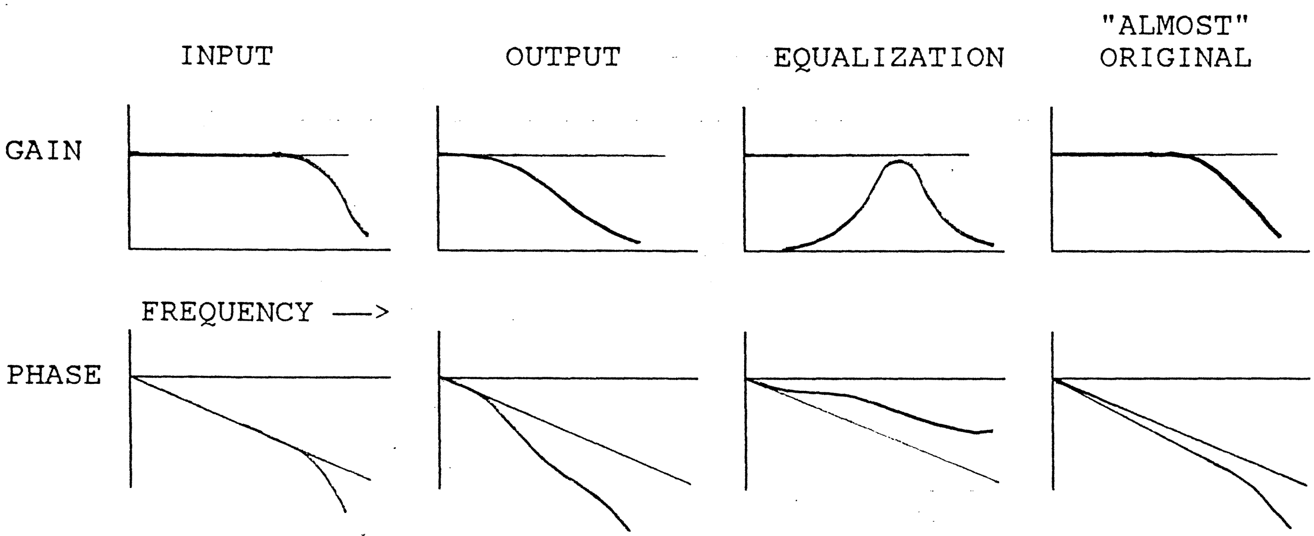


Again as the radius changes the p(t) changes and α´s and t that are optimum at the inner radius are not optimum at higher values of radii. AS FREQ CHANGES TAP CHANGES

From the frequency domain point of view intersymbol interference causes a loss at higher frequencies in the gain and a lag in the phase characteristics of the input signal.

The ideal phase characteristic is linear with frequency which results in a constant shift in the time domain independent of frequency.

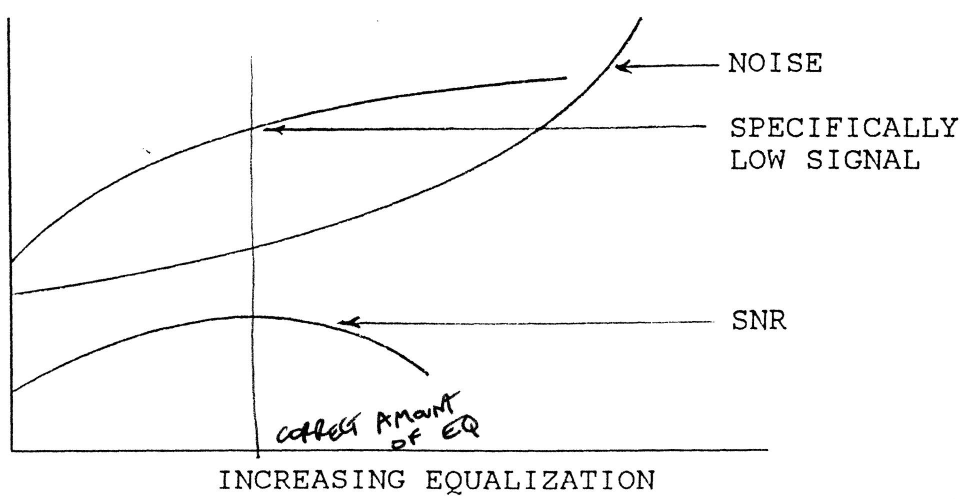
The purpose of equalization is to correct for the distortions of the channel. It can be effective over part of the frequency range.



Generally equalization boosts a frequency range where the signal is lower than desired.

There is an overall SNR loss but there can be a SNR gain for specific high error rate conditions such as the center pulse of a tri-bit.

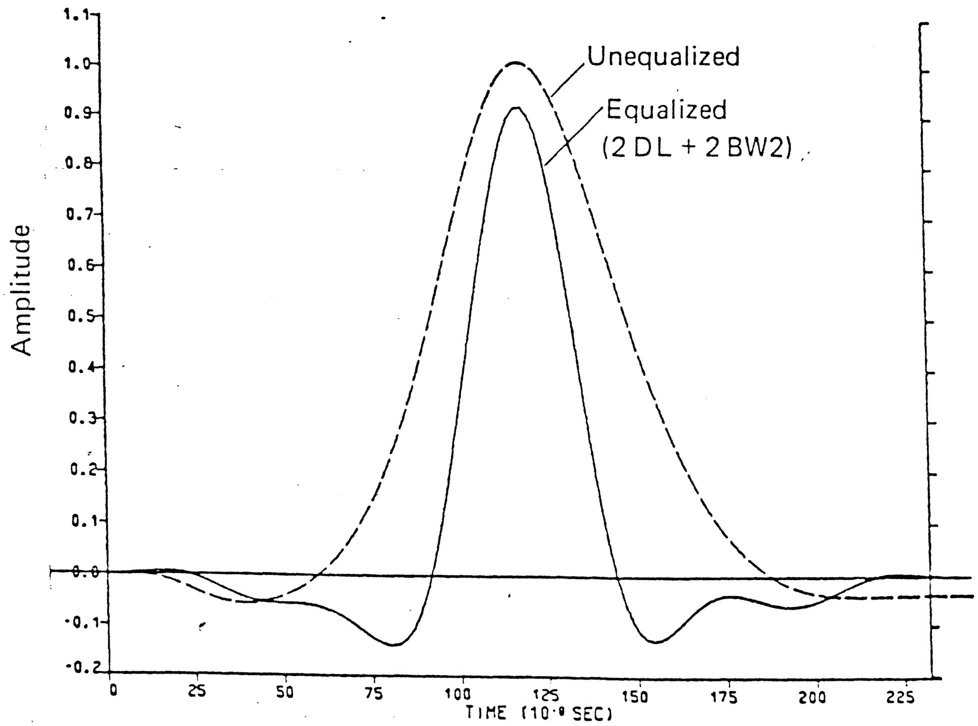
Ultimately, as the amount of equalization is increased, the noise boost will dominate, limiting the effectiveness of equalization.



It is possible to do quite a bit of pulse shaping with equalizers of several taps or stages.

In general, the more extensisive the shaping, the higher is the overall SNR loss and the more limited the gain.

Also the more difficult it is to obtain the desired equalization over a range of tolerances and especially radial position on the disk.



ISOLATED PULSE. TWO EQUALIZERS PLUS TWO BWS FILTERS

HIGHER ORDER EQUALIZATION

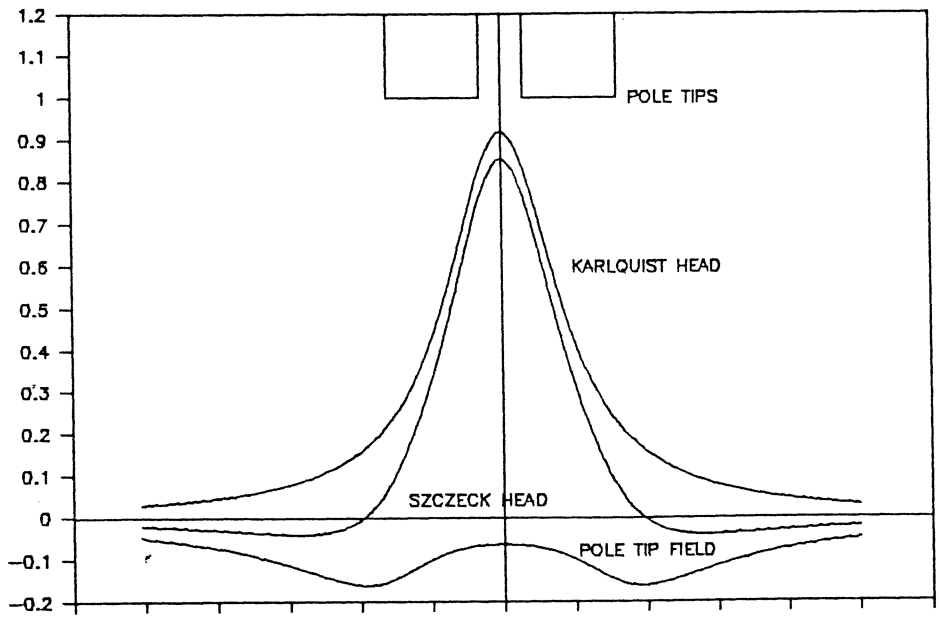
AS TRACKS ARE WIDEN'D DISK SNR INCREASES

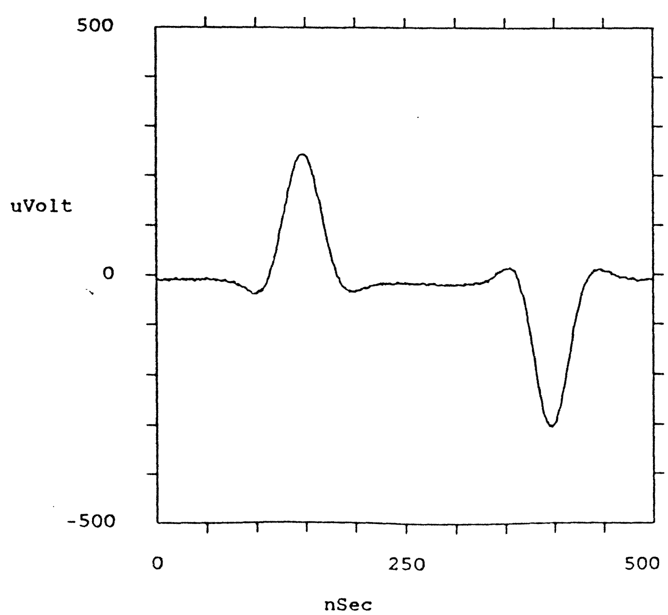
11.4 THIN FILM HEAD WITH FINITE POLE TIPS

The pole tips of the thin film head provide equalization much the same as a 2 tap dealy line. The pole tips provide a negative field or pulse.

The advantage is that the equalization is determined by geometry rather than velocity. Thus as the radius changes the equalizing effect tracks.

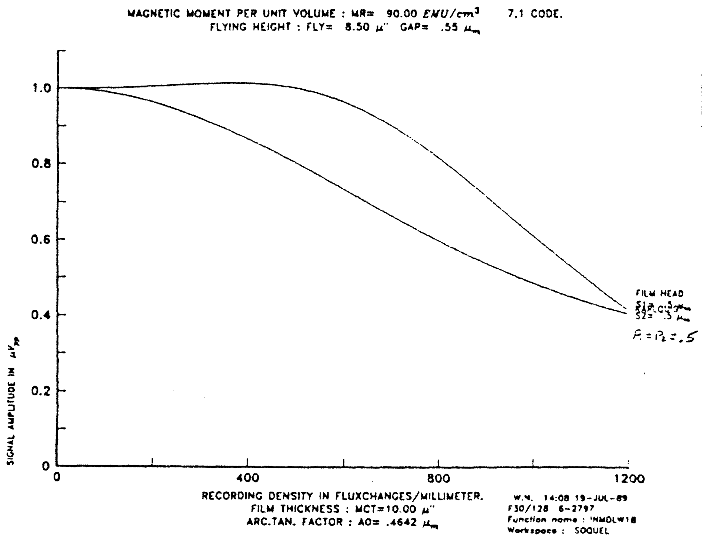
Additional equalization can be used but to a more limited extent. Additional equalization causes more undershoot and as the radius increases the undershoot eventually causes extra bit errors.

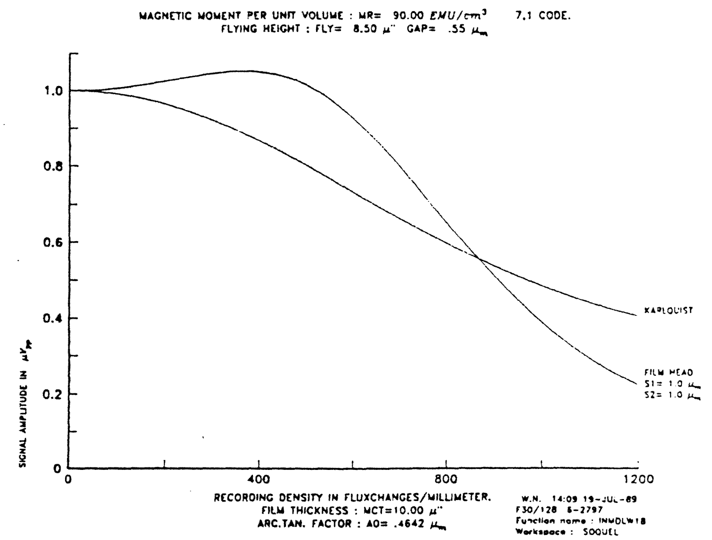


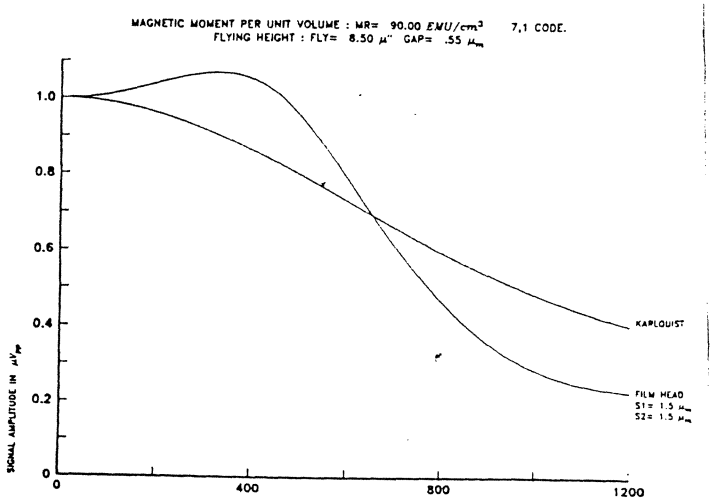


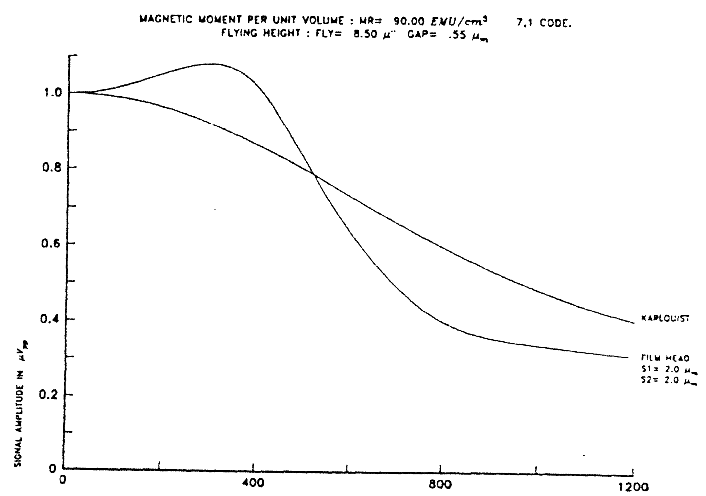
Isolated Pulse

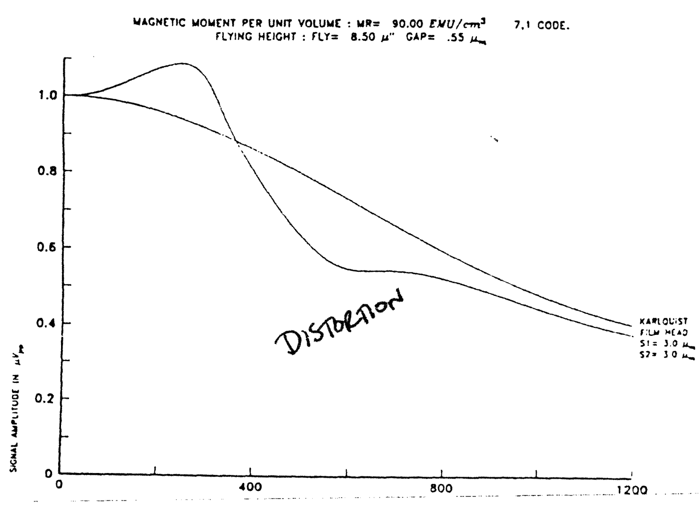
Pole/gap ratio must match the flying height and disk parameters for optimum pole tip effect.

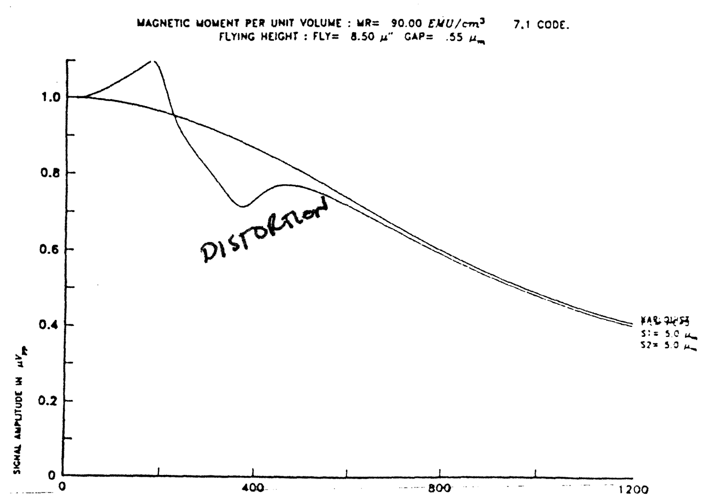












Optimum equalization matches channel spectrum to code spectrum.

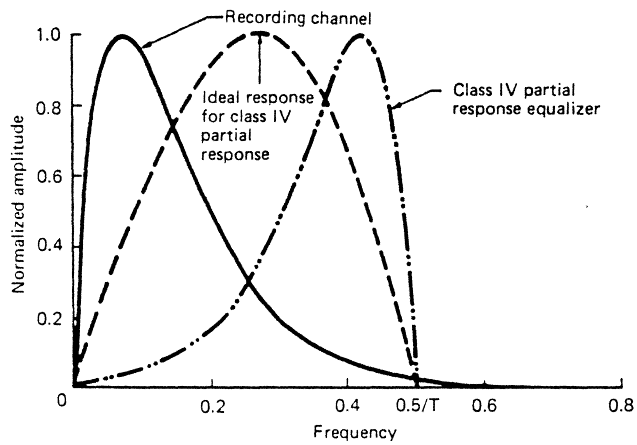
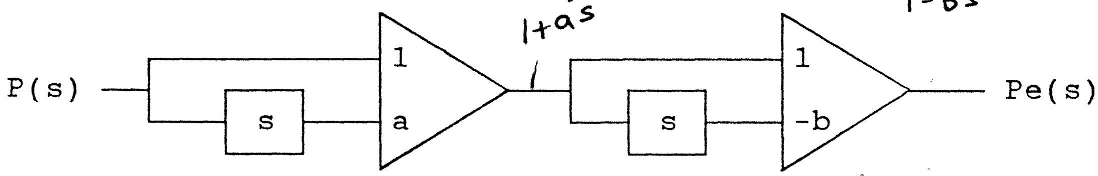


Figure 2.49 Frequency response of recording channel (before detection), ideal class IV partial response, and required class IV partial response equalizer.

PROBLEM 1. One means of generating a second derivative is with two series first derivative circuits as shown below.

1 ST DERIVATIVE

$1+as$ $\qquad$ $1-bs+as-abs^2$



a. What is the simple transfer function for this circuit? Pg 10.4

b. What is the criteria for the coeficients a, and b in order to obtain a simple second deirvative equalizer?

IF $a=b$ $\quad 1-(as)^2$

If a and b are not equal there is a first derivative term also. Sketch the first derivative of the isolated pulse shown on page 4. Under what conditions could the first derivative be of value for equalization?

$S = j\omega$

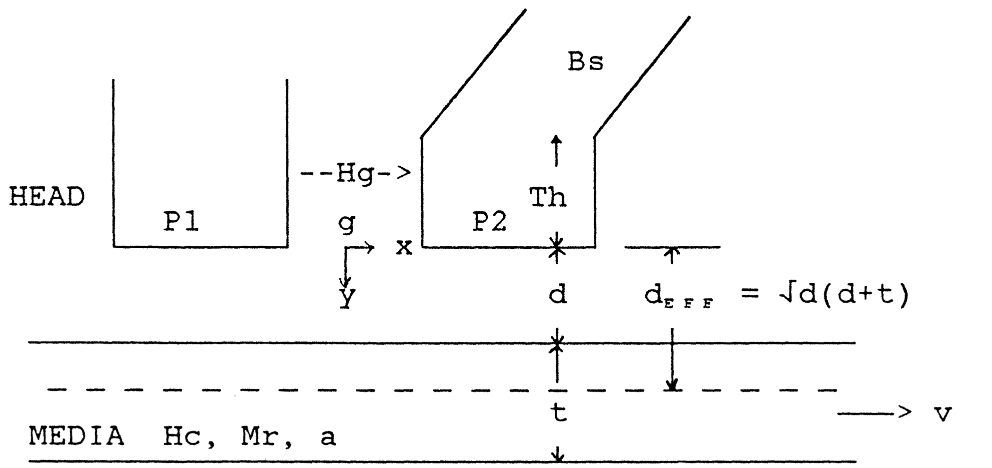
S IS A DERIVITAVE

12. LINEAR DENSITY DESIGN

12.1 KEY LINEAR DENSITY PARAMETERS

Before proceding let´s review the key head, medium, writing and reading parameters.

The key head and medium linear density parameters for the case with a thin film head are shown below.



12.2 WRITE CONDITION

The condition for adequate writing was defined in Section 6.11 in terms of the write factor Kw (6.11)

$$Kw \geq \frac{Hx(0,d_{eff}) - Hd}{Hc} \tag{12.1}$$

Combining with equation (5.11)

$$Hx(0,d_{eff}) = \frac{2H_g}{\pi} \cdot \tan^{-1}\left(\frac{g/2}{d_{eff}}\right) \geq Kw \cdot Hc + Hd \tag{12.2}$$

From equation (5.6)

$$Hg = \frac{Bs}{\mu_o} \cdot \frac{P}{Th} \tag{12.3}$$

Good writing requires large Bs, P, and g and small d and t.

12.3 READBACK

From equation (7.7)

$$Vp\text{-}p = 16 \cdot 10^{-8} \cdot N \cdot v \cdot W \cdot Mrt \cdot \frac{\varepsilon}{g} \cdot \mathrm{Atan}\left(\frac{g/2}{y_o}\right) \qquad (12.4)$$

The half pulse width is an indication of the resolution or linear density that can be achieved. It can be shown that

Density α $1/\sqrt{g^2+4d^2_{EFF}}$ for the Karlquist head. (3.6)

Density α $1/\sqrt{(P+g+P)^2+16d^2_{EFF}}$ for the Szczeck head (3.7)

Large signal requires large v, Mr, & t and small d.

High density requires small P, g, d, t, & a (small Mr, large Hc)

12.4 PARAMETER REQUIREMENTS

	P	g	Th	d	Mr	t	Hc
WRITEABILITY	LG	LG	SM	SM	SM	SM	SM
AMPLITUDE	SM	SM	SM	SM	LG	~~SM~~ LG	LG
LINEAR DENSITY	SM	SM	-	SM	SM	SM	LG

Optimum design is a set of trade-offs.

Writeability vs amplitude and density

Amplitude vs density.

Low flying and throat heights, are the only parameter that helps everything. However, head/disk mean time to failure is strongly related to d.

Thus the problem is to achieve the right balance between snr and density at the highest flying height.

Design must also include expected parameter tolerances.

We need a systematic way to see the effect of a lot of individual parameters at one time.

12.3 LINEAR DENSITY DESIGN APPROACH

The following is one approach.

It does require the help of a computer; however, the example that I will cover provides a good understanding of the trade-offs.

To do this work seriously a computer is a necessary tool.

1. Start with some initial assumptions

   Required SNR for the desired error rate and detector.

   Required resolution for the channel (including resolution)

   Achievable throat height

   Minimum write factor

   Head, disk, and channel noise values (measure if possible)

   The inner diameter velocity

   These tend to be the ones over which you have least control i.e. they are determined by physics or the state of the technology.

CAN BE CHANGED

2. Select an initial value of P and g

3. From equation 12.1 find the Hc that this head can write for the desired write factor Kw. (Estimate or neglect Hd.)

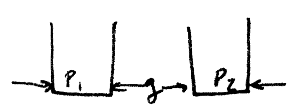
4. Select a starting value for mr and t.

5. Generate the isolated pulse from equation 3.4

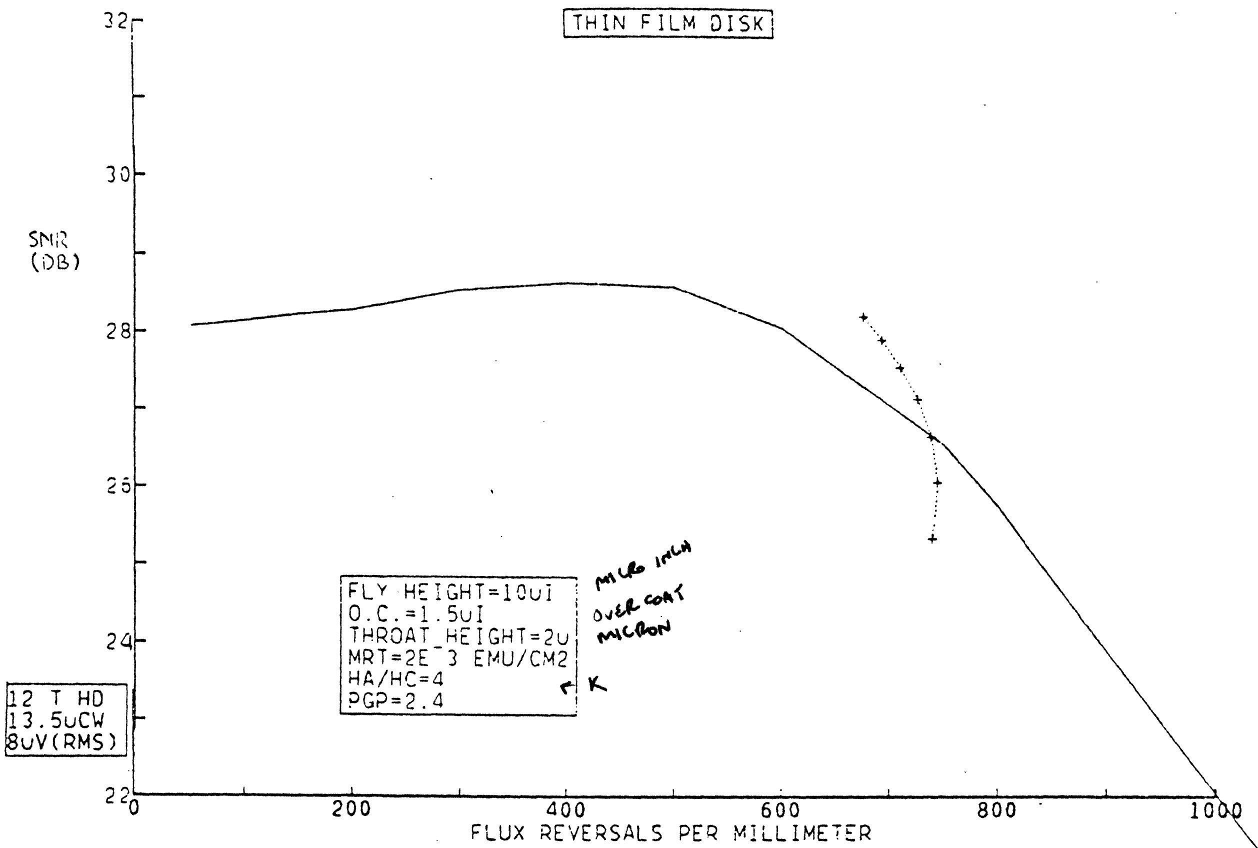
6. Generate the roll-off curve (amplitude vs density) by superposition of isolated pulses and find the density for the desired resolution.

   This point will be used to repesent the entire curve.

7. Select a range of PgP sums (constant g), repeat steps 3-6 for each and plot the resolution points. This is a curve of constant write factor. You can see the amplitide density trade off for PgP sum.



$PGP = P_1 + P_2 + g$



POINTS OF CONSTANT RESOLUTION (85%) AND CONSTANT WRITE FACTOR (4).

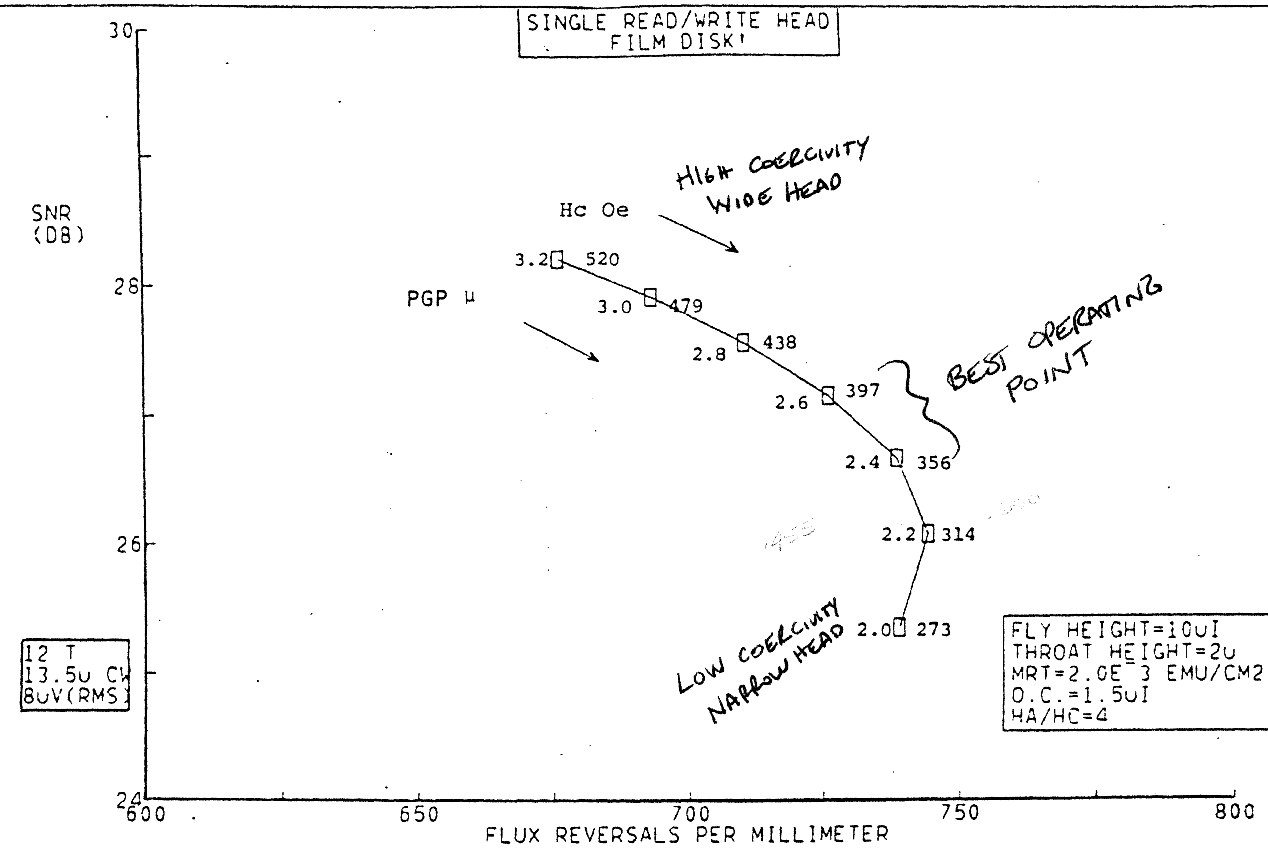
With the ordinate as SNR the picture is more complete and as the noise or track density is changed the curve will translate vertically without changing shape.

26.7 db is selected as the requirement for 2,7 code peak detection.

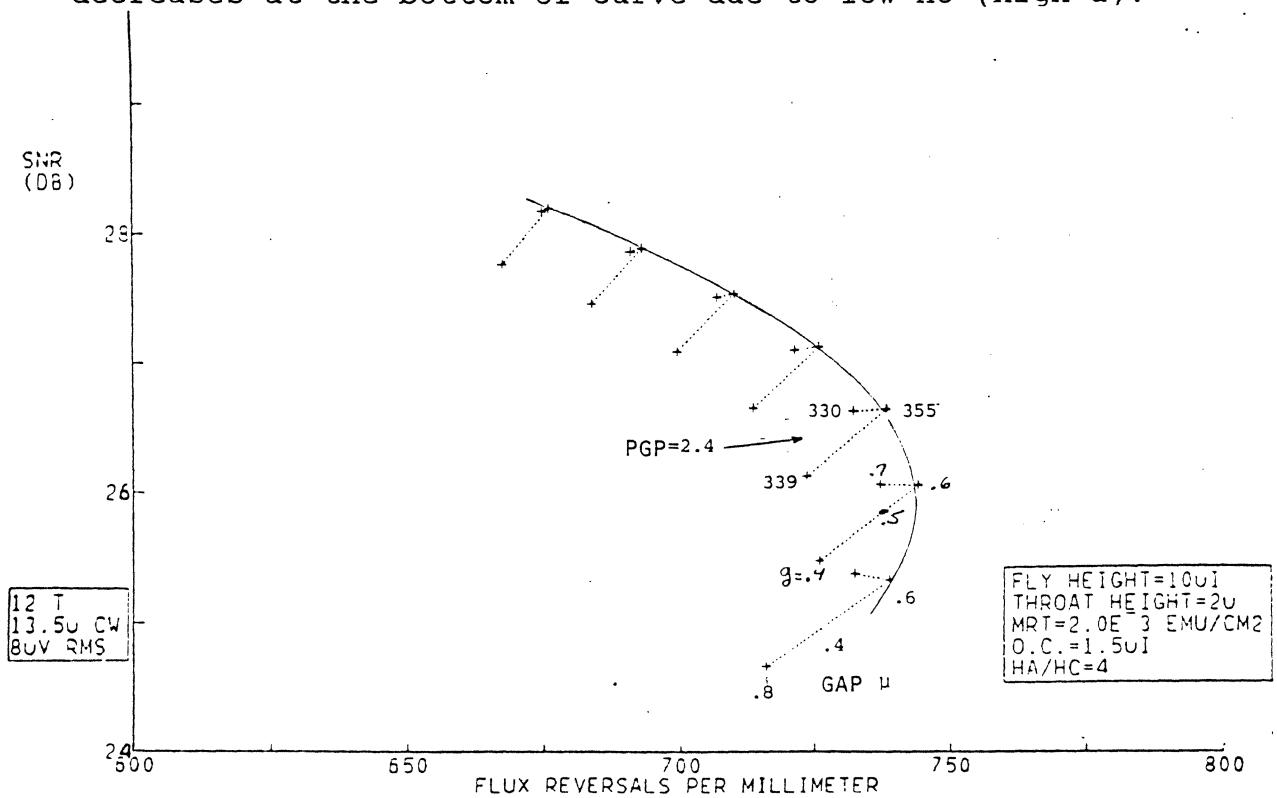
This allows for component tolerances.

The minimum requirement is more like 25 dB.

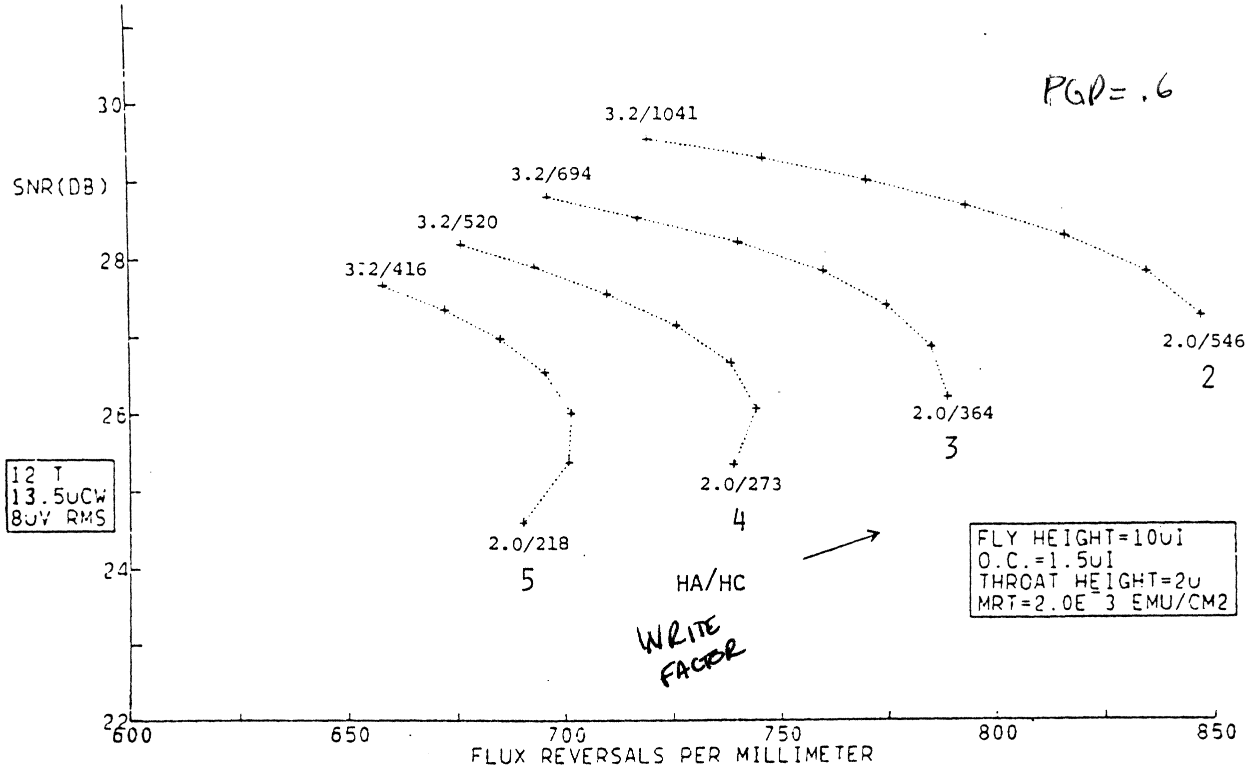
KNOW Mrt Kw
WITH PGP
CAN CALCULATE Hc



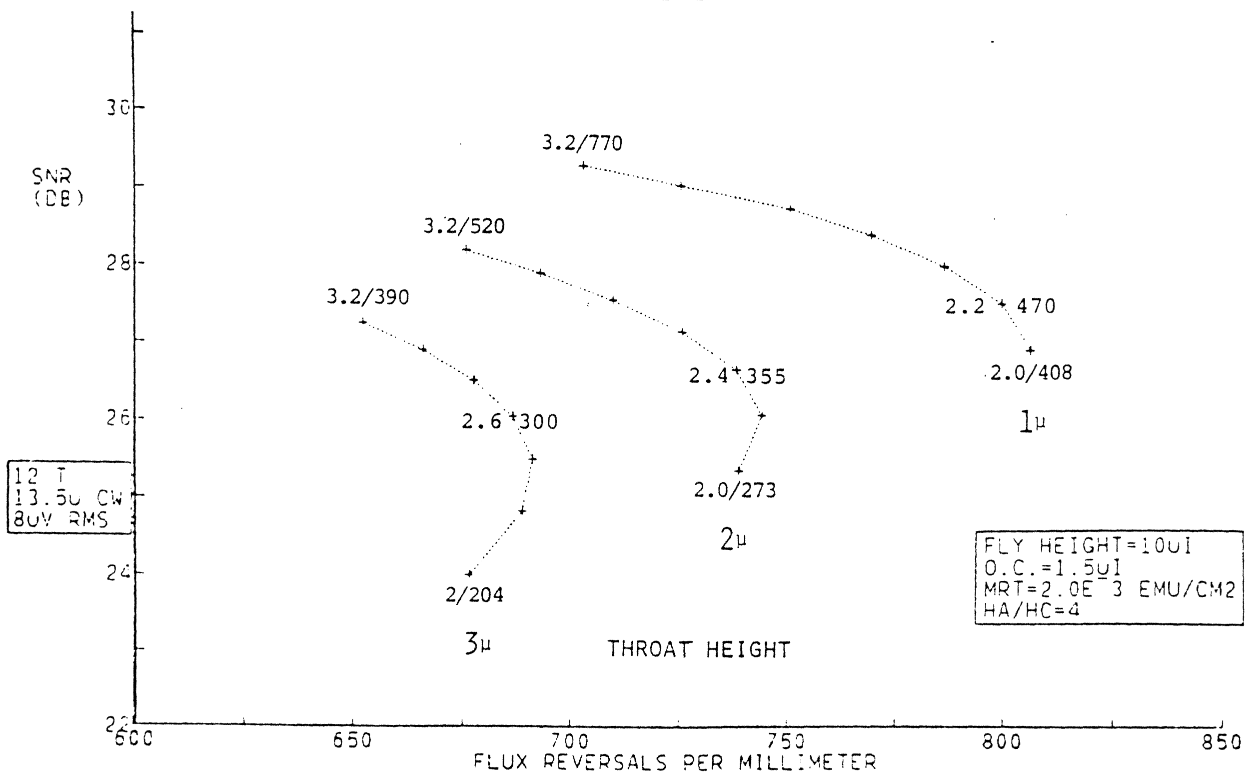
Density decreases at top of curve due to large PgP and decreases at the bottom of curve due to low Hc (high a).



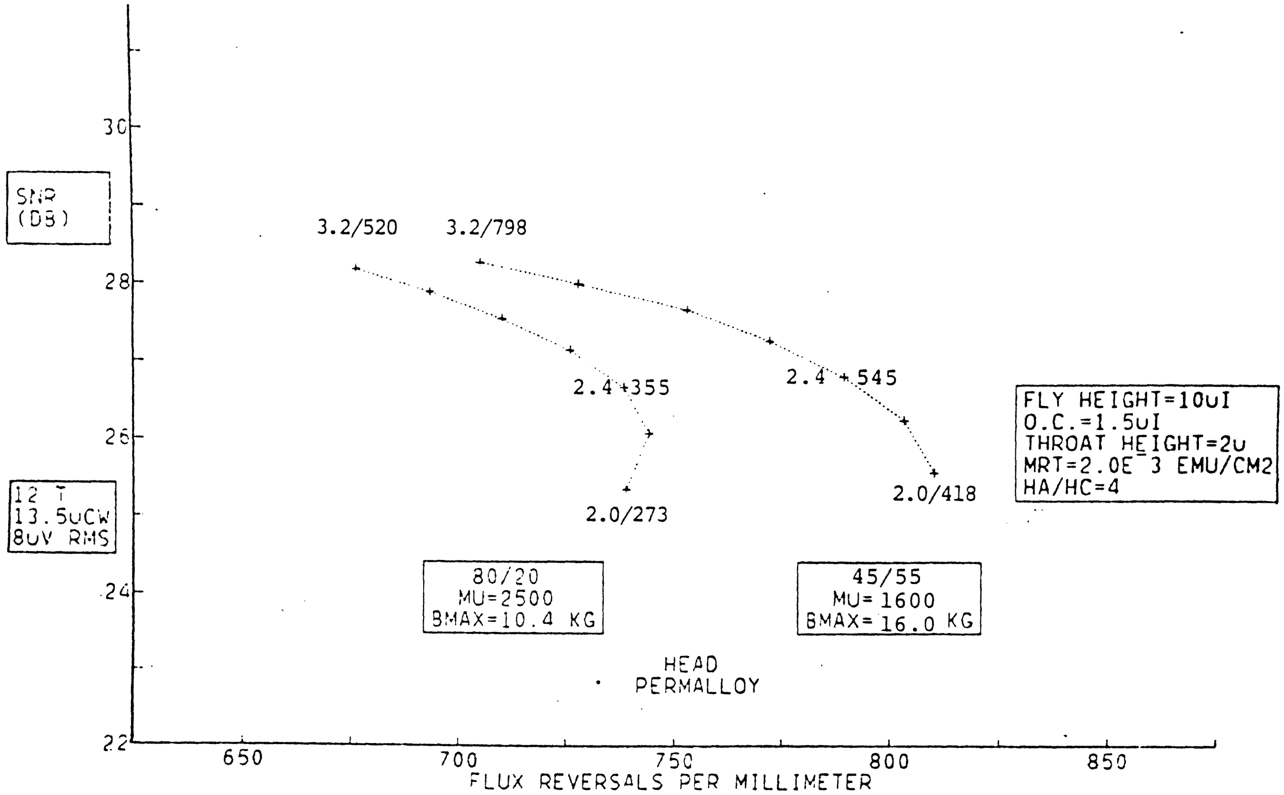
Effect of g variation with constant PgP. There is small sensitivity in range .5 to .7 µ. The selection criteria is p/g balance with spacing and how it affects the phase characteristics.



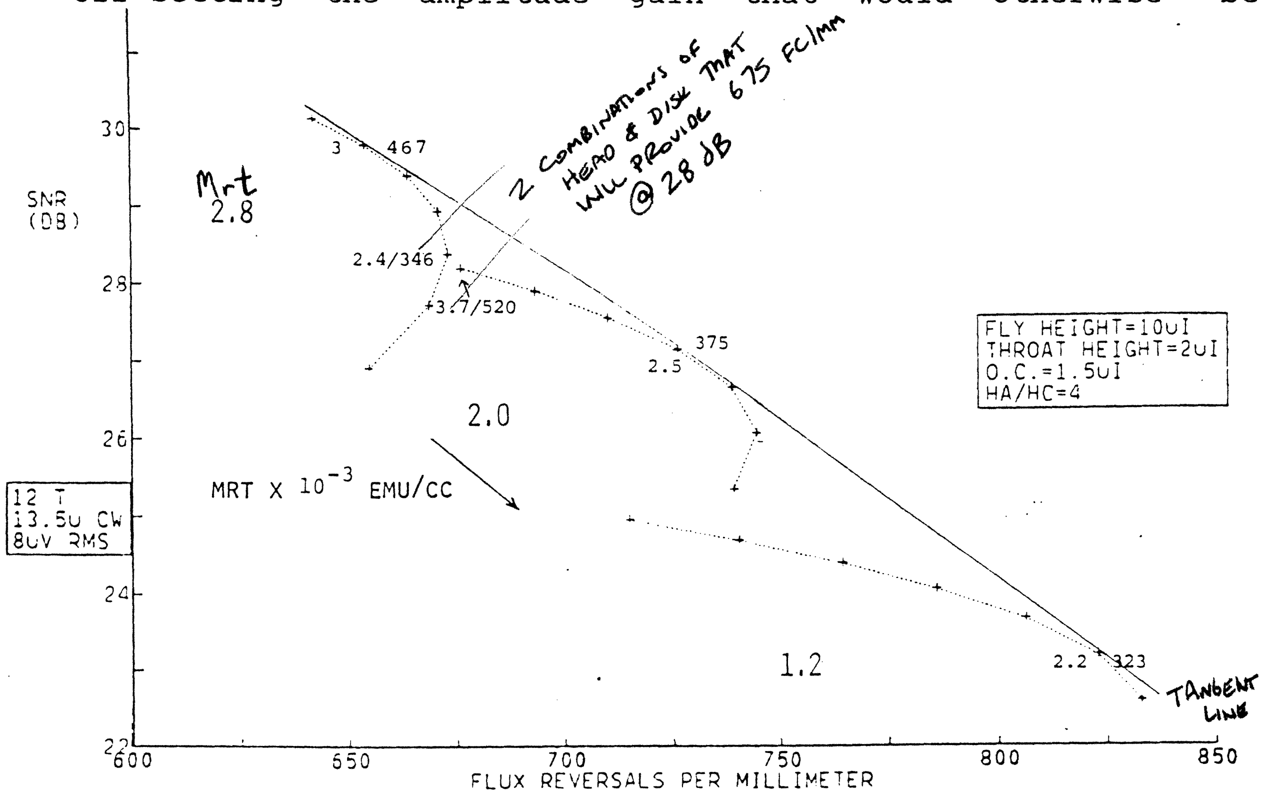
The effect of different write factors. Better writing than needed is expensive from density point of view.



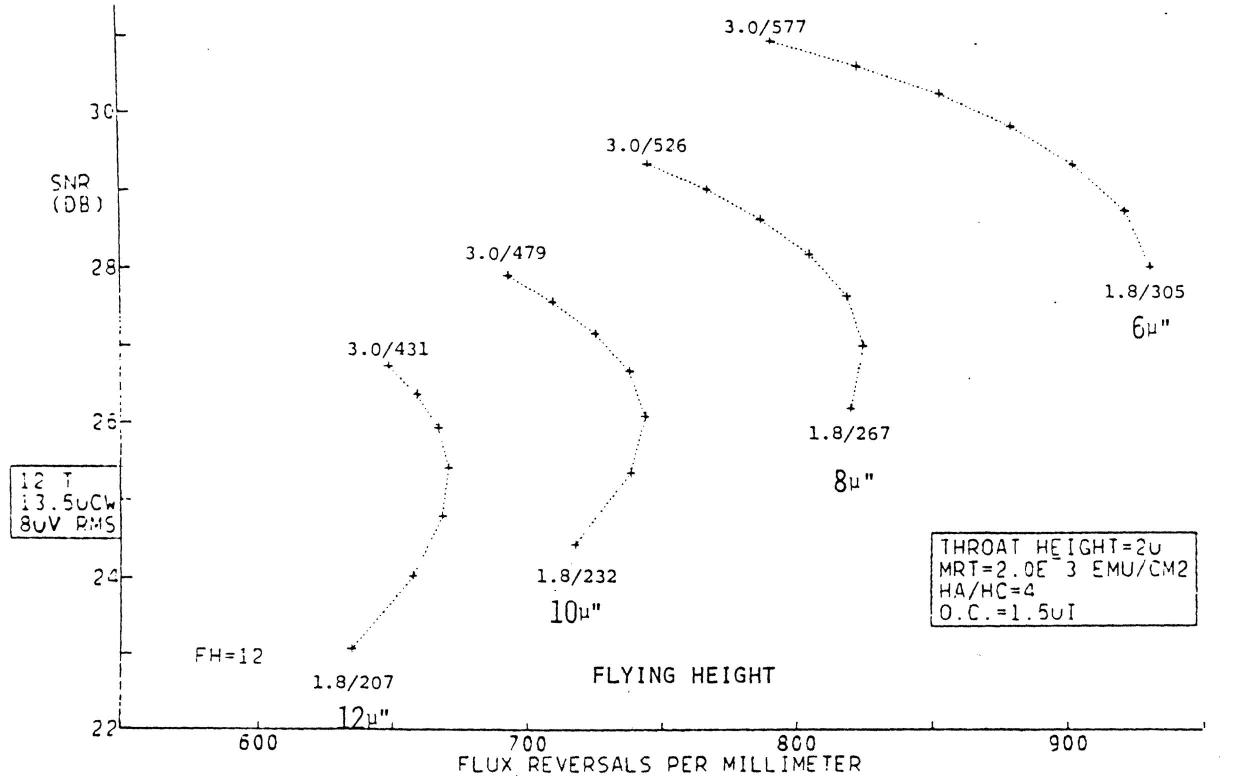
The effect of different throat heights. There is a big pay off if throat height can be kept low. The product spec will be dominated by the maximum value. Keeping the tolerance small is very important.



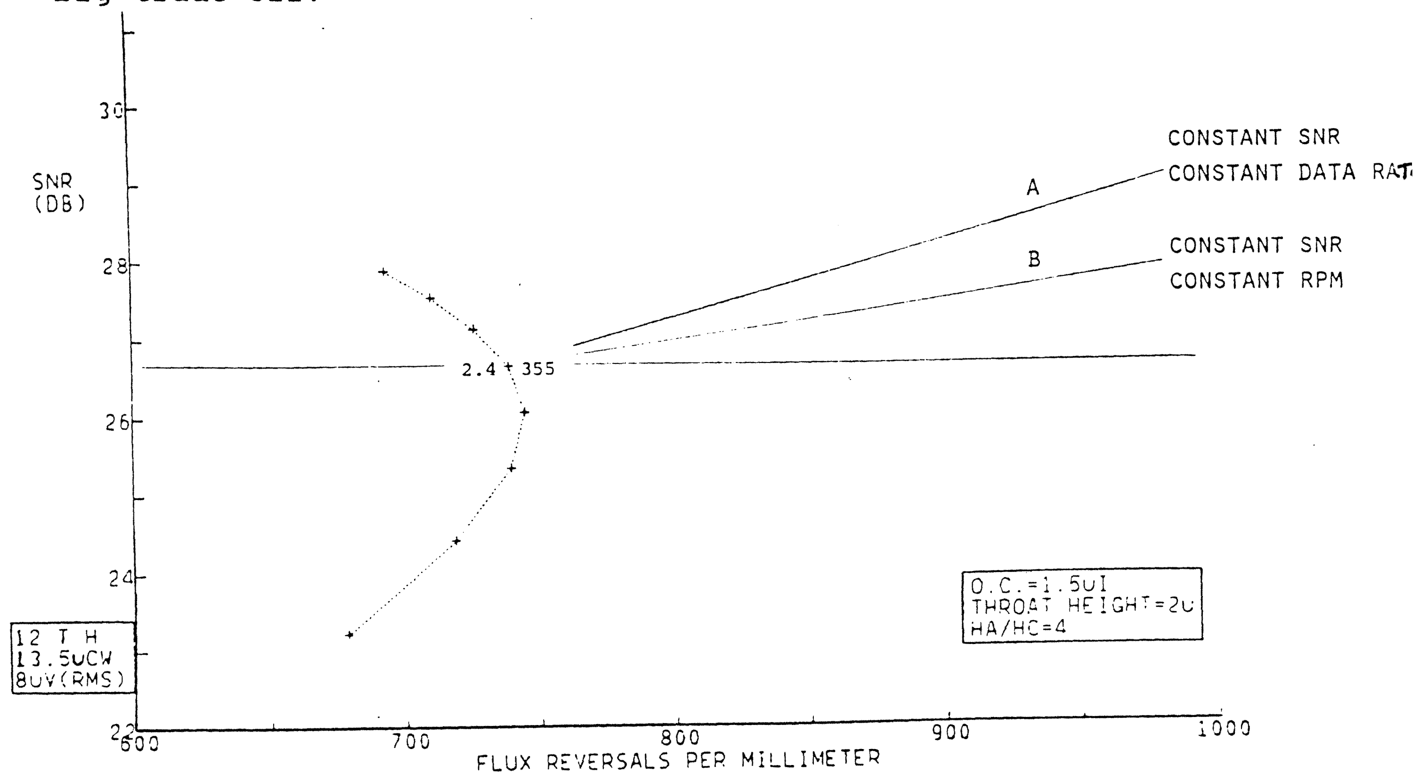
The effect of higher head Ms. In this case the matferial with the higher Ms also has a lower permeability which results in off-setting the amplitude gain that would otherwise be



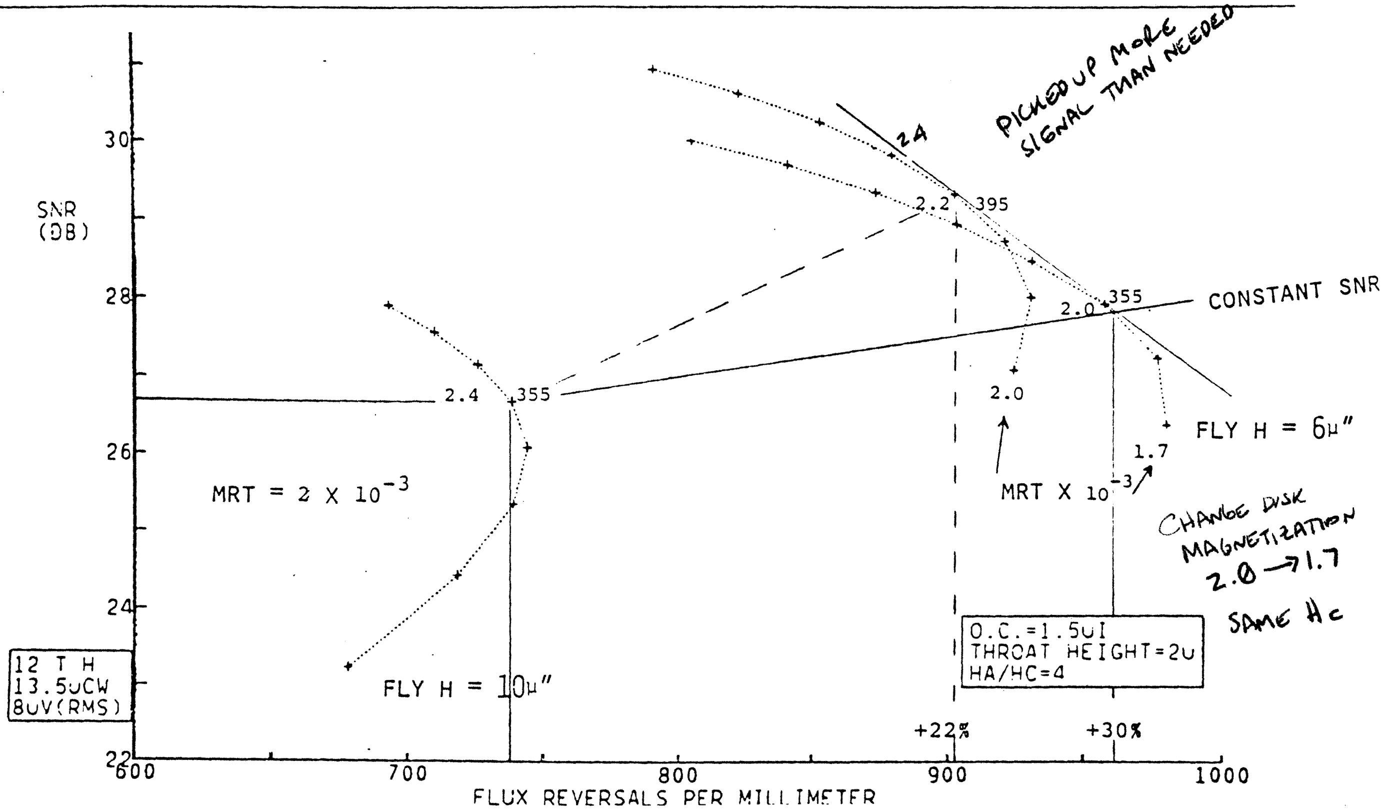
The effect of deceasing Mr of t. Note that same amplitude and density can be obtained with more than one combination of parameters. This can be confusing when there is a variety of test data. The optimum solution is on the tangent line.



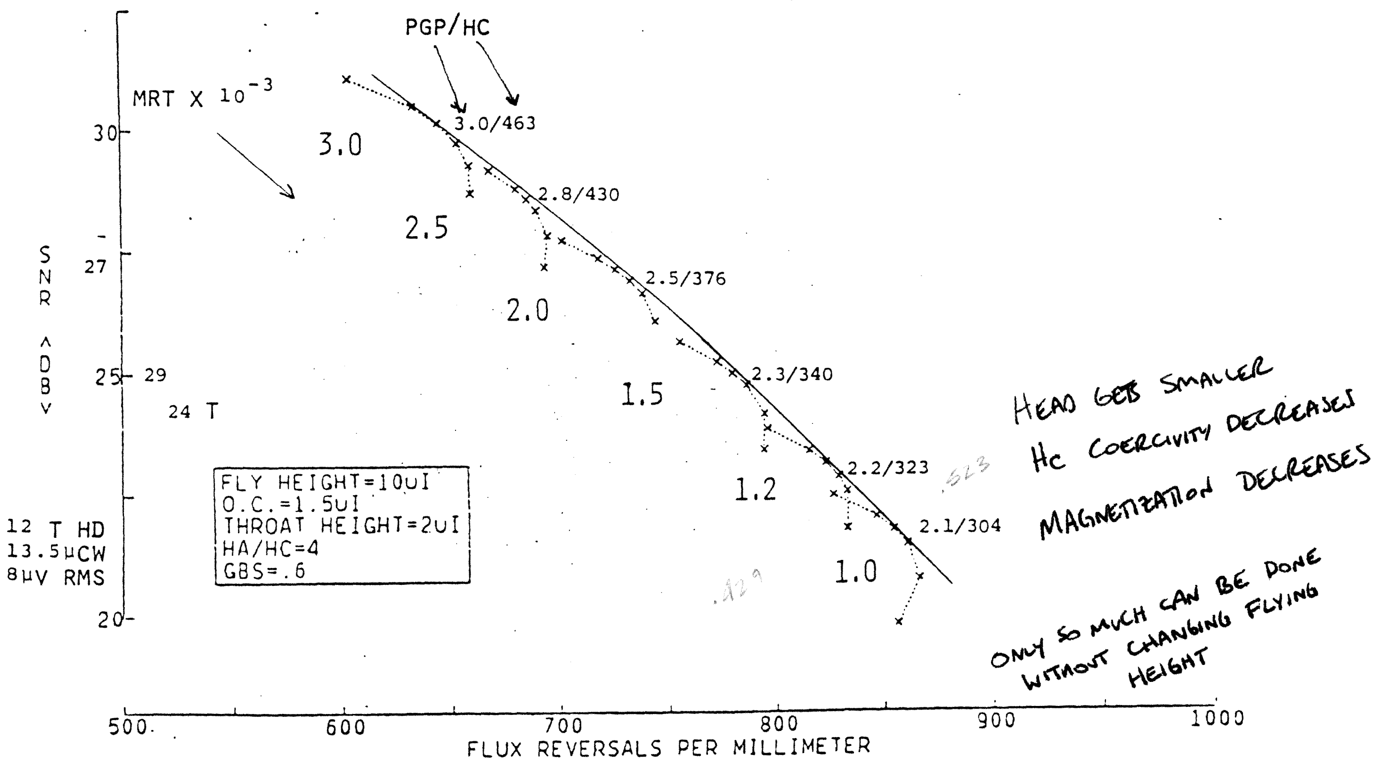
Effect decreasing the flying height. This has tremendous pay-off on both signal and density. HDA reliability is the big trade off.



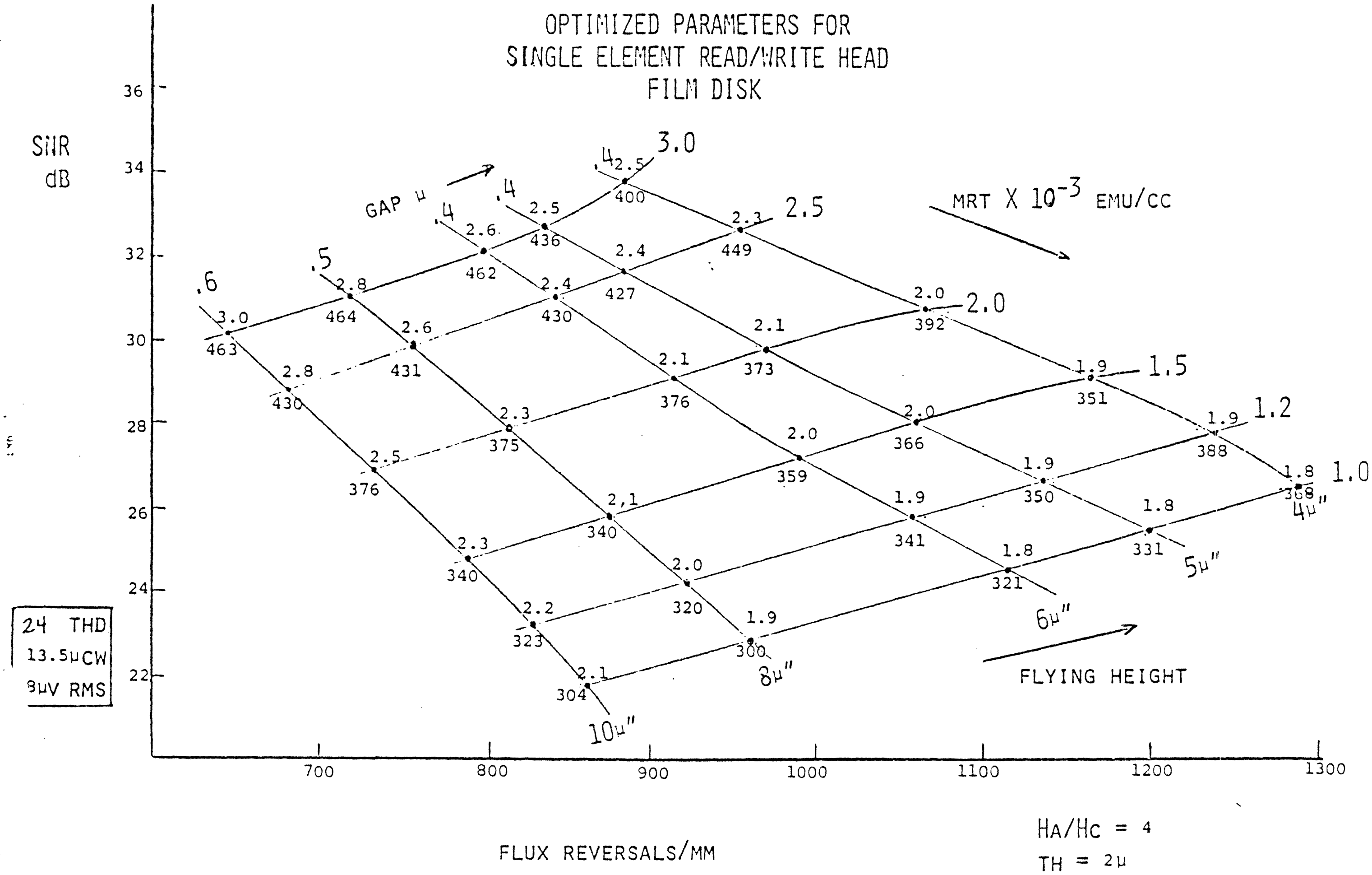
The SNR goes up faster than is required. Lines a & b represent lines of the required increase in amplitude to maintain constant SNR. In case a the velocity must decrease. In case b the data rate must increase.



To take full advantage of the decrease in flying height the Mrt, PgP and Hc should all be decreased.



A wider range of Mrt change. Note how the PgP and Hc change along the tangent line.



Mrt tangent line for different flying heights. The optimum PgP sum and Hc are given at each intersection. Note that as the flying height decreases so does the gap. The plane is for one resolution, one throat, and one write factor. If the head gain, Tw, and/or total noise change, the required SNR line can be moved up or down accodingly.

A statisticl anlaysis with a set of typical 3σ tolerance values yields the following results.

SNR -- $3\sigma/\mu$ = 2dB

DENSITY -- $3\sigma/\mu$ = .1

WRITE FACTOR -- TARGET VALUE OF 3.7 FOR A $\mu - 3\sigma$ VALUE OF 2.5.

PROBLEM 9.1

A head disk combination has a resolution of 70% at the all ones frequency. What is the dB difference in the SNR definitions of page 9.2?

Definition 1

$$SNR_1 := \frac{V_{hfrms}}{N_{rms}}$$

Definition 2

$$SNR_2 := \frac{V_{lfbp}}{N_{rms}}$$

$$\frac{SNR_1}{SNR_2} = \frac{V_{hfrms}}{V_{lfbp}} = \frac{V_{hfrms}}{V_{hfbp}} \times \frac{V_{hfbp}}{V_{lfbp}} = \frac{1}{\sqrt{2}} \cdot .7 = 0.495$$

$20 \cdot \log(.495) = -6.108$ dB difference

PROBLEM 9.2

a. Derive an equation for the unit media noise (UMN) a a function of disk SNR and track width W.

Unit media noise (UMN) is defined as $\dfrac{N_{rms}}{Ps\cdot\sqrt{W}}$

$$SNR := 20\cdot\log\left[\frac{S}{N}\right] \quad , \quad .05\cdot SNR := \log\left[\frac{S}{N}\right] \;\square\; , \quad 10^{.05\cdot SNR} = \frac{S}{N}$$

$$N := \frac{S}{10^{.05\cdot SNR}} \quad , \quad \frac{N}{W} = \left[\frac{\frac{S}{W}}{10^{.05\cdot SNR}}\right] = \frac{Ps}{10^{.05\cdot SNR}}$$

$$\frac{N}{Ps\cdot\sqrt{W}} = \frac{\sqrt{W}}{10^{.05\cdot SNR}} = UMN$$

b. The SNR for a disk type is advertized as 33 dB for W = 10 μ. What is the UMN?

$SNR := 33$ dB

$W := 10$ μ

$$UMN := \frac{\sqrt{W}}{10^{.05\cdot SNR}}$$

$UMN = 0.071$ $\sqrt{\mu}$

c. You want to use this disk in a product with W = 6 μ. You measure the Vp-p as 700 μV. What is the disk noise and SNR under these conditions?

$W_2 := 6$ μ

$S := \dfrac{700}{2}$ μVb-p

$Ps := \dfrac{S}{W_2}$ μV/μ

$Ps = 58.333$ μV/μ

$N := UMN\cdot Ps\cdot\sqrt{W_2}$

$N = 10.116$ μV rms

PROBLEM 9.3

The noise of an amplifier is measured with the input shorted and found to have a noise voltage of 6 μV rms with a 30 MHz bandwidth. The noise of a head and this amplifier to gether is found to be 8.5 μV rms at30 MHz. What is the head noise for a bandwidth of 20 MHz?

$N_a := 6$

$BW_1 := 30$

$BW_2 := 20$

$$\sqrt{N_a + N_h} = 8.5$$

$$N_h := \sqrt{8.5^2 - 6^2} \cdot \sqrt{\frac{BW_2}{BW_1}}$$

$N_h = 4.916$

PROBLEM 9.4

A given disk is stated to have a SNR of 30 dB when measeured at 40 MHz with the head and amplifier of problem 3 and with W = 10 μ.

a. If the low frequency peak to peak signal is 600 μV, what is the disk noise in μV?

b. What is the total SNR if you use this disk with a similar head with W = 8μ and at a bandwidth of 30 MHz.

PROBLEM 9.4

$$SNR_d := 30$$

$$BW_1 := 40$$

$$W_1 := 10$$

a.

$$S_{Lfbp1} := \frac{600}{2}$$

From 9.2

$$N_{d1} := \frac{S_{Lfbp1}}{10^{.05 \cdot SNR_d}}$$

$$N_{d1} = 9.487 \quad \mu V \text{ rms}$$

b.

$$W_2 := 8$$

$$BW_2 := 30$$

$$N_{d2} := N_{d1} \cdot \sqrt{\frac{W_2}{W_1}}$$

$$N_{d2} = 8.485$$

$$N_{e1} := 8.5 \qquad \text{from 9.3}$$

$$S_{Lfbp2} := S_{Lfbp1} \cdot \left[\frac{W_2}{W_1}\right]$$

$$S_{Lfbp2} = 240$$

$$SNR_2 := 20 \cdot \log\left[\frac{S_{Lfbp2}}{\sqrt{N_{d2}^2 + N_{e1}^2}}\right] \qquad SNR_2 = 26.013 \quad \text{dB}$$

PROBLEM 9.5

When measured on a test stand at 40 MHz, a disk has a noise of 8.5 μV rms, the head and amplifier have a combined noise of 10 μV and the Vp-p is 500 μV.

$BW_1 := 40$ $N_{d1} := 8.5$

$N_{e1} := 10$

a. What is the dB SNR of the combination is used in a channel with a BW of 27 MHz?

$BW_2 := 27$

$S_1 := \frac{500}{\sqrt{2}}$

$N_{e2} := N_{e1} \cdot \sqrt{\frac{BW_2}{BW_1}}$

$N_{e2} = 8.216$

$SNR_1 := 20 \cdot \log\left[\frac{S_1}{\sqrt{N_{d1}^2 + N_{e2}^2}}\right]$

$SNR_1 = 26.505$

b. What is the approximate on track error rate (OTER) with a 2,7 code peak detection channel?

SNR at the detector = $SNR_1 - 11.4 = 15.105$ dB

From the CEF OTER = 1E-8

PROBLEM 9.6

a. If the data rate for the components of problem 9.5 were increased requiring a bandwidth of 40 MHz, what would be the loss in dB and the new on track error rate?

$BW_2 := 40$ $\qquad$ $SNR_1 = 26.505$

$N_e := 10$

$$SNR_2 := 20 \cdot \log\left[\frac{S_1}{\sqrt{N_{d1}^{\,2} + N_e^{\,2}}}\right]$$

$SNR_2 = 25.597$

$LOSS := SNR_1 - SNR_2$

$LOSS = 0.908$ dB

$SNR_2 - 11.4 = 14.197$ $\qquad$ OTER for SNR2 = about 2E-7

b. In addition to the higher data rate, it is desired to increase the the track density requiring W = 8μ. What is the loss in SNR due to both changes and what is the new projected on track error rate?

$W_1 := 10$

$W_2 := 8.5$

$$N_{d2} := N_{d1} \cdot \sqrt{\frac{W_2}{W_1}} \qquad S_2 := S_1 \cdot \left[\frac{W_2}{W_1}\right]$$

$N_{d2} = 7.837$ $\qquad$ $S_2 = 212.5$

$$SNR_3 := 20 \cdot \log\left[\frac{S_2}{\sqrt{N_{d2}^{\,2} + N_e^{\,2}}}\right]$$

$SNR_3 = 24.468$

$LOSS := SNR_1 - SNR_3$

$LOSS = 2.037$

$SNR_3 - 11.4 = 13.068$

From the CEF OTER = 1E-5

PROBLEM 9.6 Continued

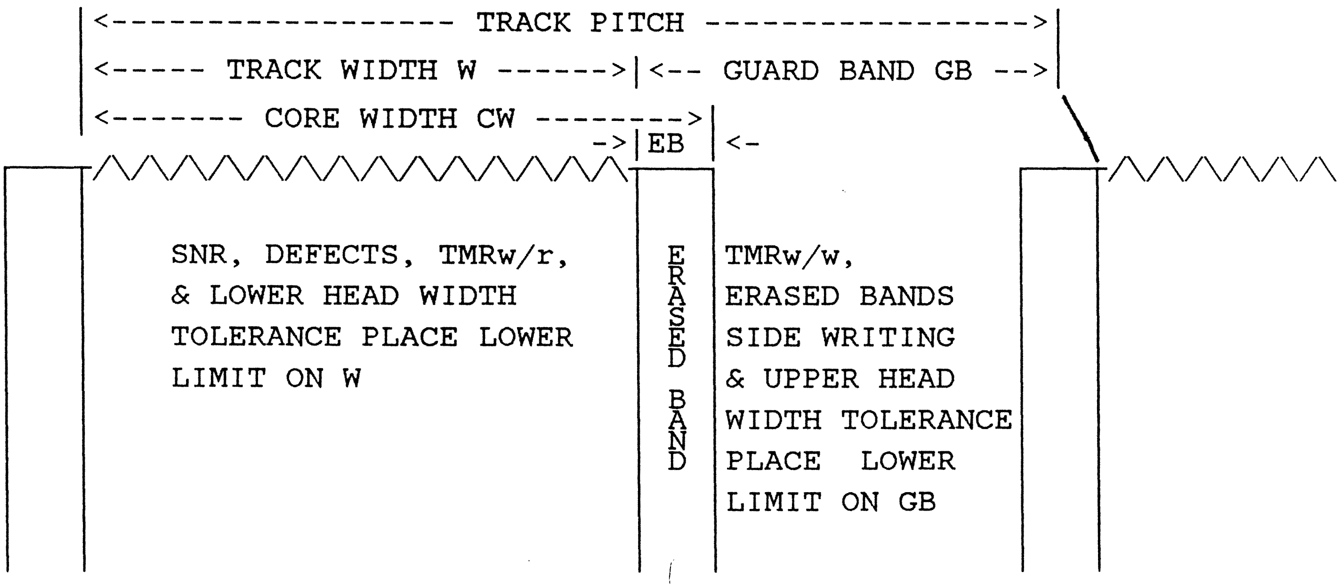
c. What would you recommend about making these changes?

Either one is marginal both are unsatisfactory.

TRACK DENSITY DESIGN

TRACK DENSITY LIMITERS

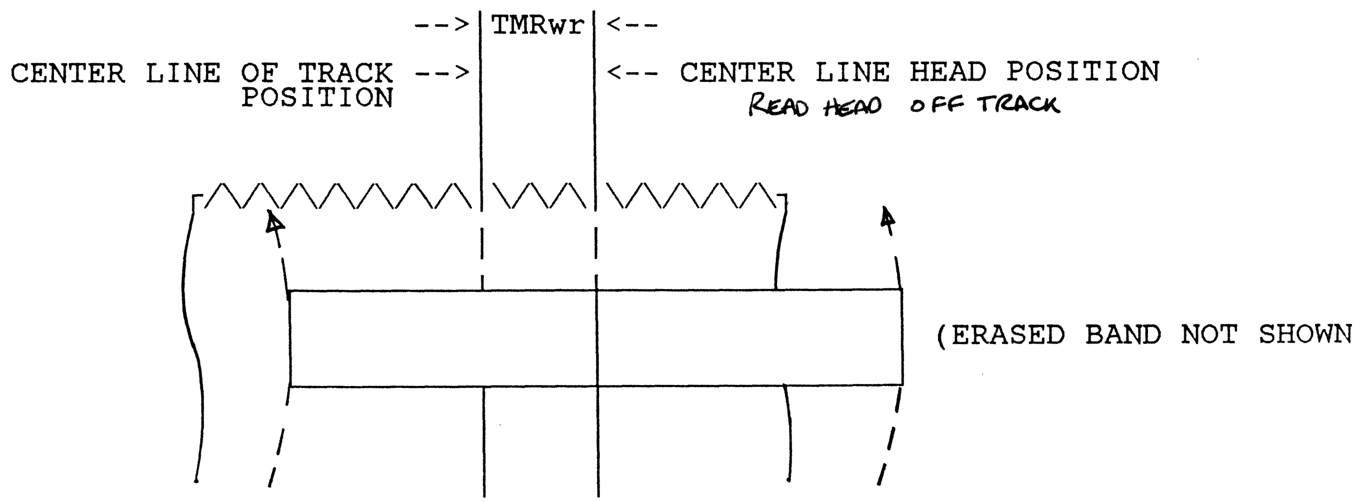
- SNR
- DISK DEFECTS
- TRACK MISREGISTRATION (TMR) WRITE TO READ
- HEAD WIDTH TOLERANCES
- HEAD SIDE WRITING AND READING



SIDE WRITING EFFECT

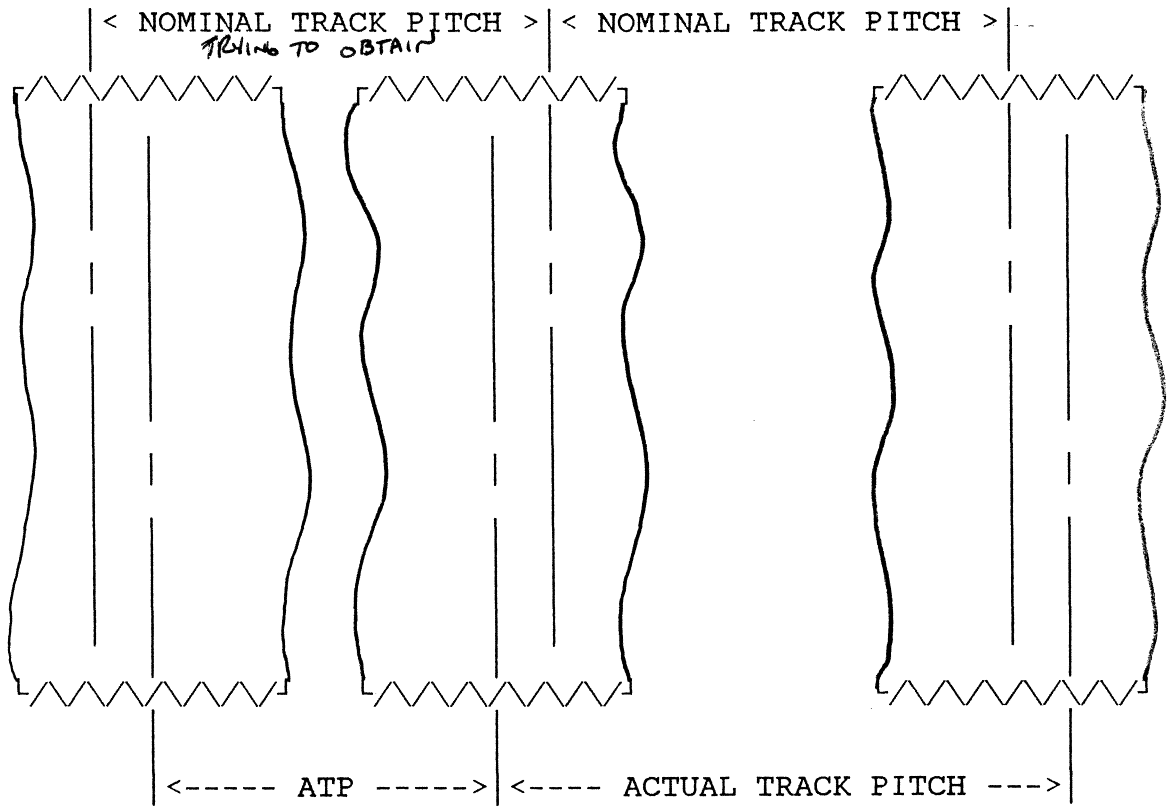
TRACK MISREGISTRATION (TMR)

- **TMR WRITE TO READ, TMRw/r**



- TMRw/r IS THE 3σ VALUE OF THE DIFFERENCE BETWEEN THE HEAD AND THE ACTUAL TRACK LOCATION -- NOT THE NOMINAL OR IDEAL LOCATION.

- **TMR WRITE TO WRITE, TMRw/w**

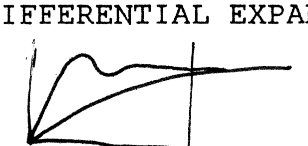


- **TMRw/w IS THE 3σ VALUE OF (NOMINAL TRACK PITCH - ATP)**

- $\text{TMRw/w} = \left[\text{TMRw/r}^2 + \text{THE TMR OF THE SERVO WRITER}^2\right]^{1/2}$

  THE SERVO TRACKS, WHICH ARE THE REFERENCE FOR READING AND WRITING IN A GIVEN FILE HAVE THEIR OWN VARIATIONS IN ADDITION TO THE SOURCES OF TMR WITHIN THE FILE.

- THE PRIMARY SOURCES OF TMR ARE:
  - o NON REPEATABLE RUN OUT OF THE SPINDLE (BEARINGS)
  - o THERMAL EFFECTS -- DIFFERENTIAL EXPANSION
  - o WEAR
  - o SERVO SETTLING



- TMR VALUES ARE IN THE LOW MICRON RANGE

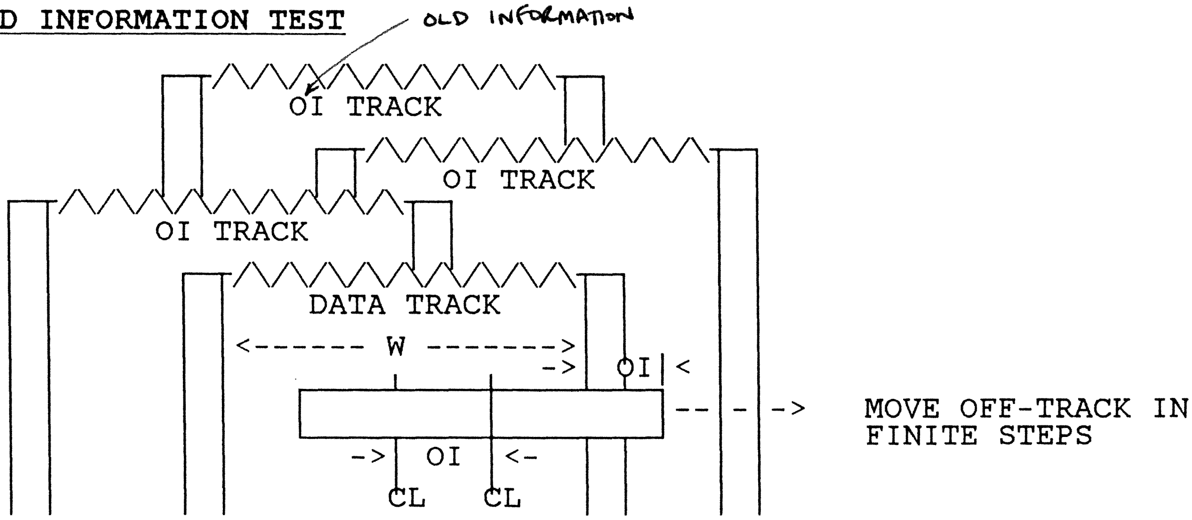
TRACK DENSITY AND ERROR RATE ASSESSMENT TESTS

- QUICK ASSESSMENT OF TRACK DENSITY
  - OLD INFORMATION TEST
  - TRACK PITCH AT FAILURE TEST
  - LAMBDA CURVE ANALYSIS
- OPTIMIUM TRACK DENSITY FOR GIVEN HEAD/DISK
  - 747 CURVE
- ERROR RATE DETERMINATION
  - BATHTUB CURVE
  - SQUEEZE CURVE
  - TMR/ERROR RATE ANALYSIS

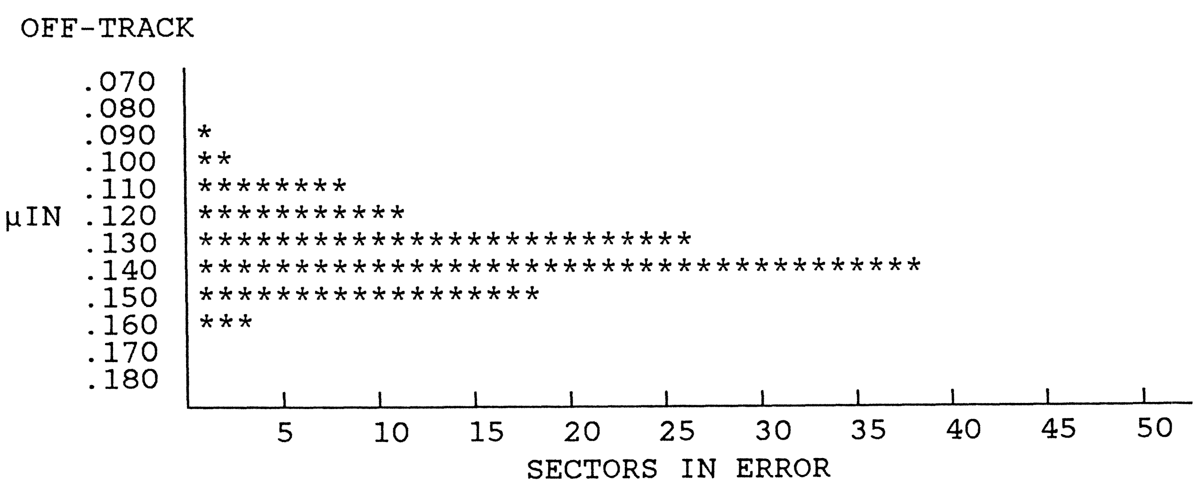
TRACK WIDTH AND PITCH BOUNDARIES

- THE OLD INFORMATION AND TRACK PITCH AT FAILURE TESTS DETERMINE THE EFFECTIVE OR CORE WIDTH OF A HEAD AND TOGETHER WITH THE TMRs AN ESTIMATE OF THE MINIMUM TRACK PITCH CAN BE MADE.

- <u>OLD INFORMATION TEST</u>



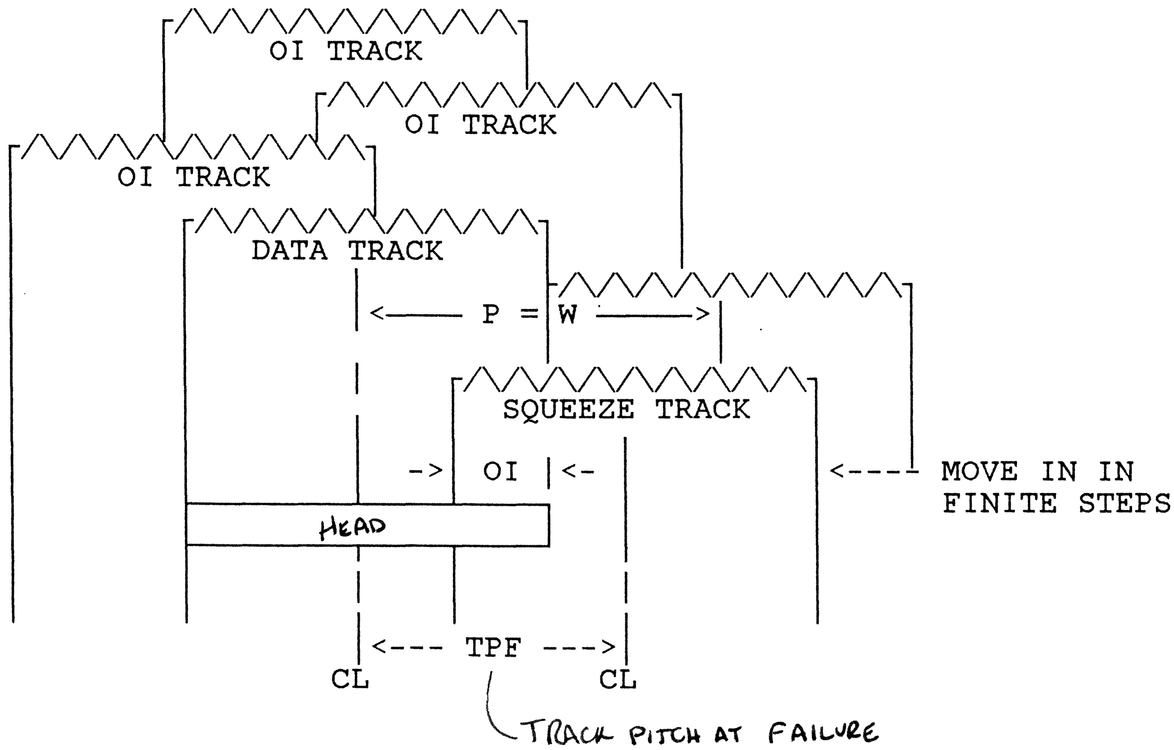
- OLD INFORMATION AND DATA TRACKS ARE WRITTEN AS SHOWN.
- DATA TRACK IS DIVIDED INTO A NUMBER OF SECTORS.
- A SECTOR, BYTE FAILURE CRITERIA IS SET.
- AS THE HEAD MOVES OFF-TRACK IN FINITE STEPS, THE SECTORS THAT FAIL ARE COUNTED AND THEN MASKED. 0 POSITION IS ON-TRACK.
- THE PROCEDURE IS RUN IN EACH DIRECTION.
- MULTIPLE TRACK SETS ARE RUN AS PART OF THE SAME TEST FOR LARGER SAMPLE SIZE.



MIN = .090 MAX = .160 **AVE = .134** SIGMA = .013 SAMPLE = 100

- **´THE IO´ ≡ AVE OF THE SECTOR FAILURE HISTOGRAM,**
- **AT THIS POINT W IS NOT KNOW**

- **TRACK PITCH AT FAILURE**



- OLD INFORMATION AND DATA TRACKS ARE WRITTEN AS WITH THE OI TEST

- AN ADJACENT TRACK IS MOVED IN IN FINITE STEPS AND FAILED SECTORS ARE COUNTED PER STEP AND MASKED. ALL READING IS ON-TRACK. THE KNOWN MEASUREMENT IS CENTER LINE TO CENTER LINE.

- THE TEST PRODUCES A HISTOGRAM SIMILAR TO THE OI TEST BUT WITH THE TRACK PITCH AS THE ORDINATE.

- **TPF ≡ THE TRACK PITCH AT THE MEAN OF THE SECTOR FAILURE HISTOGRAM.**

- IT IS SEEN THAT FROM THE DIAGRAM THAT

$$W = TPF + OI_{TPF} \qquad \text{BUT } OI_{TPF} \text{ IS NOT KNOWN.}$$

- SINCE THE HEAD SEES THE SAME AREA OF DATA AND OLD INFORMATION IN BOTH OI AND TPF TESTS, ONE MAY ASSUME

$$OI_{OI} = OI_{TPF}$$

- SO

$$\mathbf{W \text{ OR CORE WIDTH} = TPF + OI_{OI}} \qquad \text{IS NOW KNOWN} \tag{4.1}$$

$$\mathbf{ALPHA,}\ \alpha \equiv \frac{\mathbf{OI}}{\mathbf{OI + TPF}} = \frac{IO}{W} = \text{THE OFF-TRACK PERCENTAGE} \tag{4.2}$$

- IF ERASED BANDS ARE INCLUDED, W WILL BE = W + **1** EB.

- **MINIMUM W AND TRACK PITCH P**

  - GOODNESS IS LARGER OI, SMALL TPF, LARGE α AND SMALL P.
  - A FINITE EB IS DESIRABLE
  - OI IS A MEASURE OF HOW FAR IT IS OK FOR THE HEAD TO MOVE.
  - TMRwr IS A MEASURE OF HOW FAR OFF-TRACK THE HEAD WILL MOVE.
  - THUS

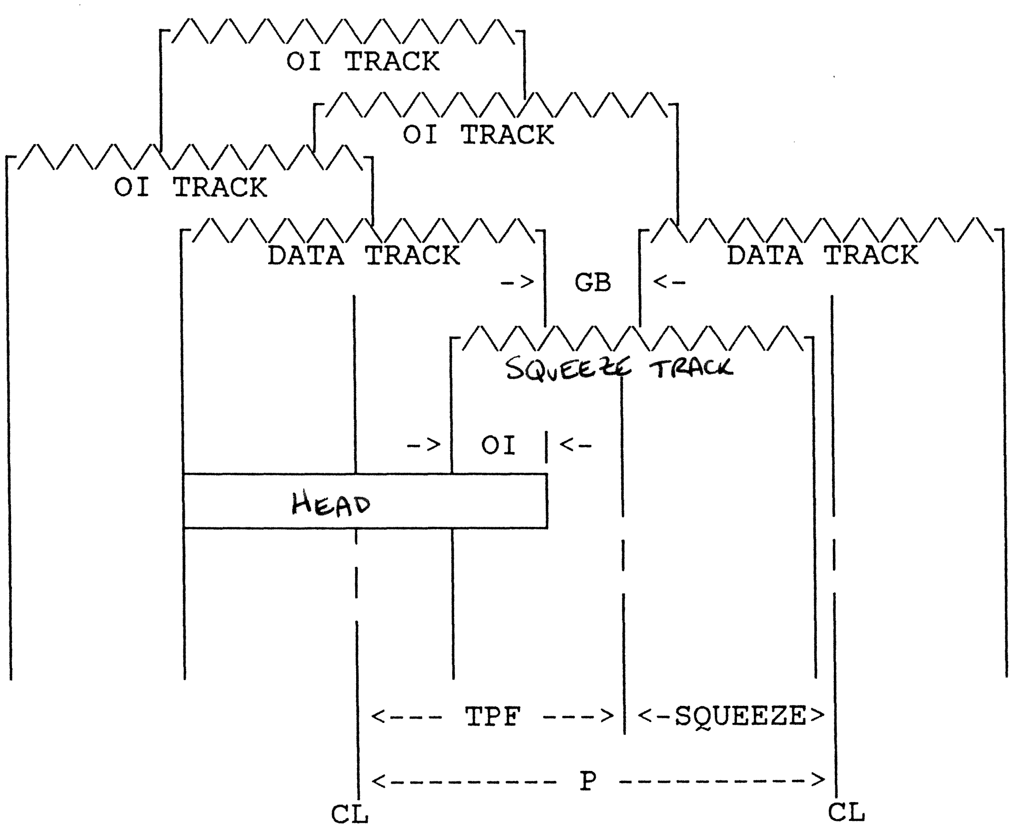
$$\mathbf{OI > k_1 TMRw/r} \quad \text{OI WILL INCREASE AS W INCREASES} \qquad (13.3)$$

COMBINING WITH (3.2)

$$\mathbf{CW > k_1 TMR/\alpha} \qquad (13.4)$$

k_1 IS A CONSTANT THAT DEPENDS OF THE DEFINITION OF THE SECTOR FAILURE CRITERIA. k_1 IS 1.3 - 1.5 OR SO WHEN THE BYTE ERROR RATE OF THE OI CRITERIA IS E-4.

- CONSIDER ANOTHER DATA TRACK AT A **POTENTIAL** TRACK PITCH P.



- **SQ ≡ P - TPF** (13.5)

  IS A MEASURE OF HOW FAR AWAY FROM NOMINAL IT IS OK FOR THE ADJACENT TRACK TO BE WRITTEN

- FROM EQUATION 13.5

$$P = SQ + TPF \qquad (13.6)$$

- ALSO

$$P = CW - EB + GB \quad \text{AND}$$

$$SQ = GB - EB + IO$$

- SO

$$CW - OI = P - SQ$$

$$CW = (P-SQ)/(1-\alpha) \qquad (13.7)$$

- TMRw/w IS A MEASURE OF HOW FAR AWAY FROM NOMINAL THE ADJACENT TRACK WILL BE WRITTEN

- THUS

$$SQ > k_2\, TMRw/w \qquad (13.8)$$

AND

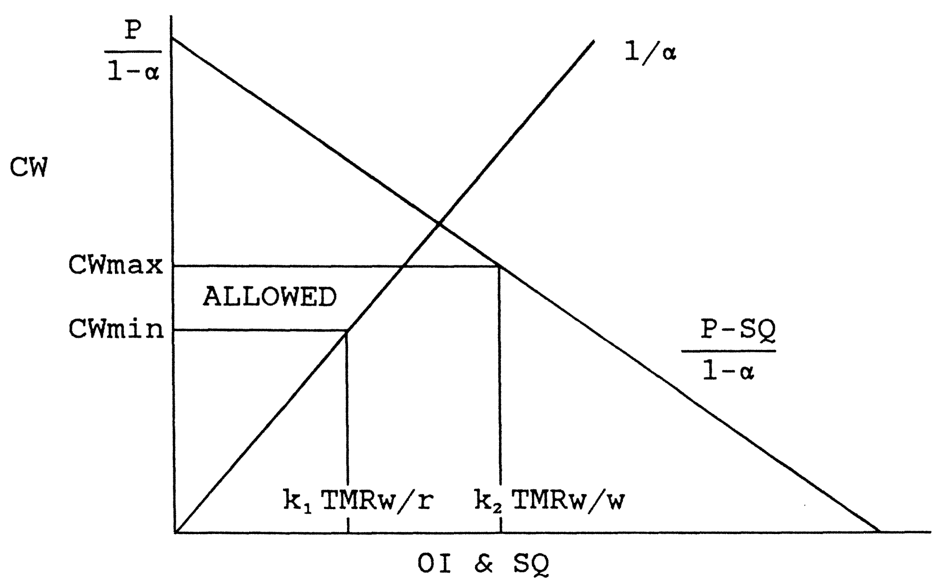
$$P \geq TPF + k_2 \cdot TMRw/w$$

- FROM EQUATIONS 13.4, 13.6, 13.7 AND 13.8 WE GET

α IS % OFFTRACK ALLOWED

$$k_1 \cdot TMRw/r \leq CW \leq \frac{(P - k_2 \cdot TMRw/w)}{1-\alpha} \qquad (13.9)$$

- PLOTTING EQUATIONS 13.2 AND 13.7 GIVES A PICTURE OF THE SITUATION.

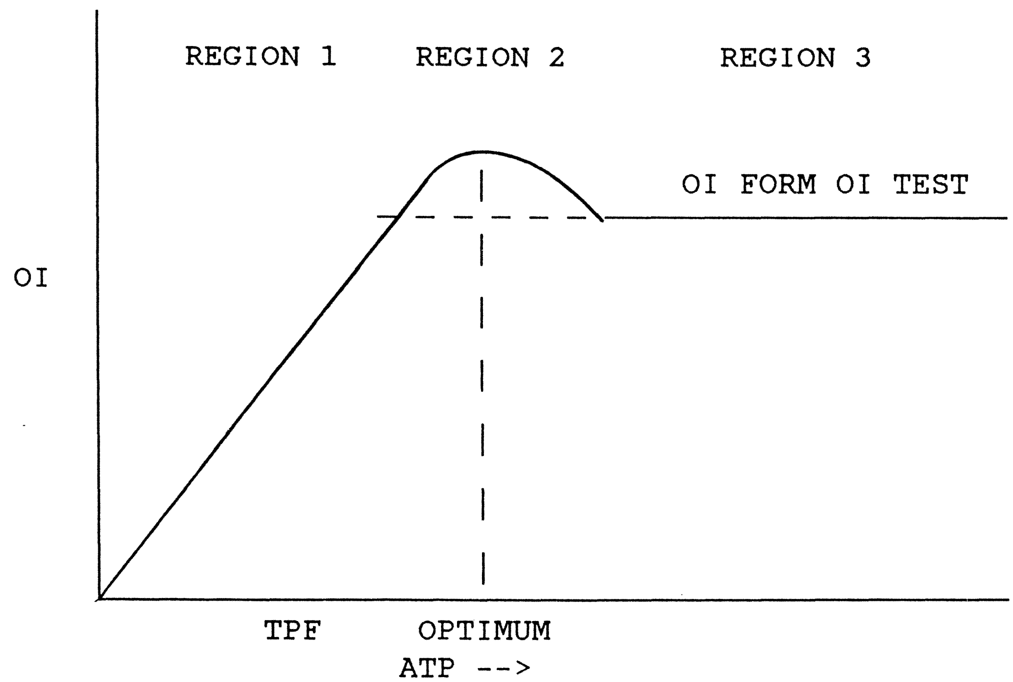


THIS IS CALLED A LAMBDA CURVE. IT GIVES A QUICK SIZING OF THE ADEQUACY OF A GIVEN HEAD FOR A GIVEN TRACK PITCH. IT DOES NOT GIVE OPTIMUM VALUES NOR DOES IT ALLOW PREDICTIONS FOR OTHER HEADS SINCE α MAY CHANGE IF W CHANGES.

747 CURVE

- THE 747 CURVE IS THE PRIMARY TEST THAT IS USED TO OPTIMIZE THE WIDTH OF A HEAD TO A GIVEN TRACK PITCH.

- THE CURVE IS GENERTATED BY REPEATING THE OLD INFORMATION TEST WHILE CHANGING THE PITCH OF AN ADJACENT TRACK STARTING FROM A FAIRLY LARGE VALUE OF PITCH. IT IS LIKE THE TPF TEST EXCEPT THAT THE HEAD MOVES OFF-TRACK AND A VALUE OF OI IS DETERMINED FOR EACH ADJACENT TRACK PITCH (ATP).



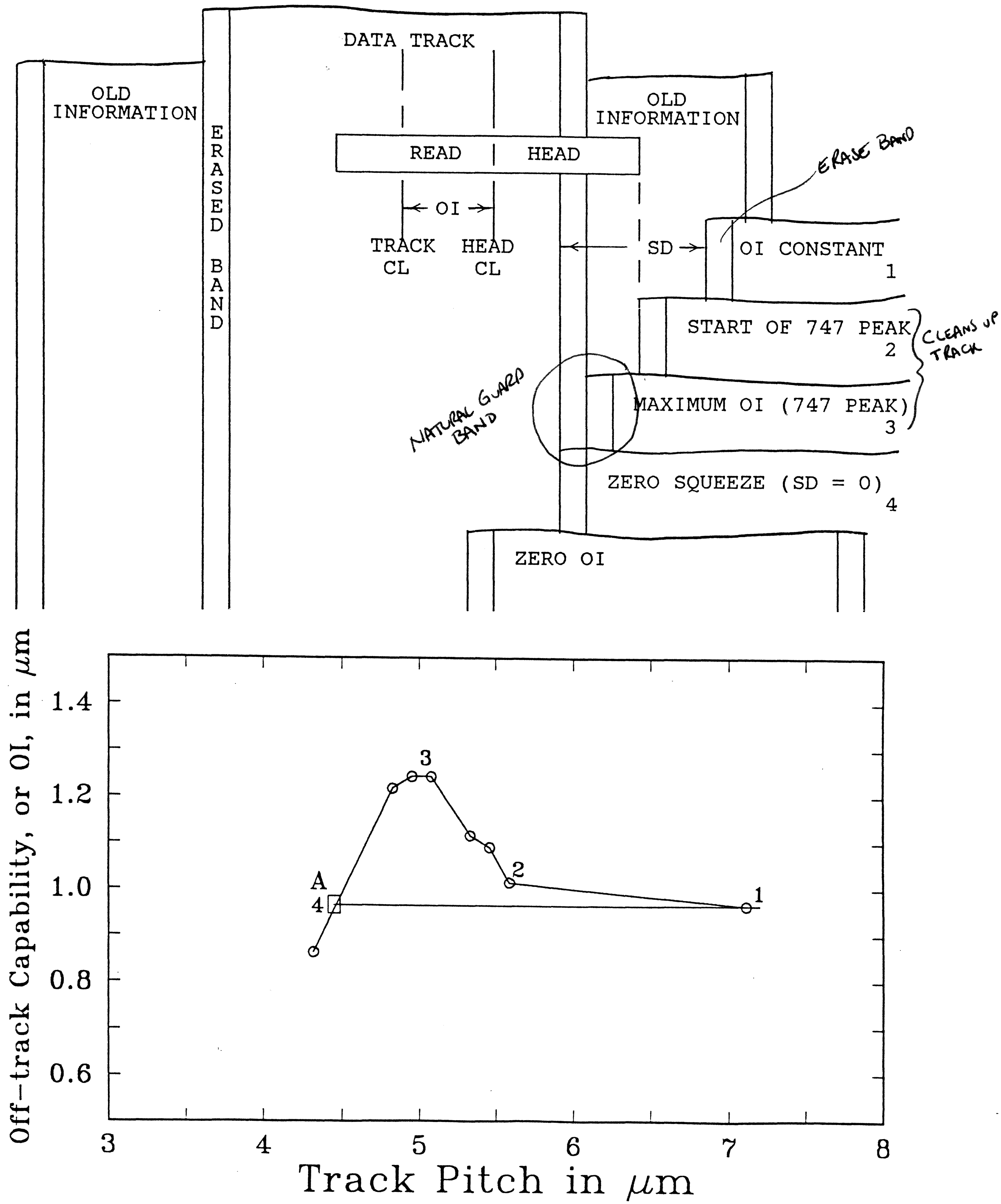
- THE OPTIMUM PITCH IS WHERE THE OI IS THE GREATEST. IF THIS IS NOT THE PITCH THAT YOU WANT, YOU MUST CHANGE THE HEAD WIDTH.

- FOR A NARROWER HEAD BOTH THE OPTIMUM PITCH AND THE CORRESPONDING OI WILL DECREASE.

- ALL OF THE INFORMATION OBTAINED WITH LAMBDA CURVE IS OBTAINED HERE PLUS MUCH MORE; HOWEVER, THE TEST TAKES MUCH LONGER.

- THE 747 CURVE IS USUALLY RUN FOR SEVERAL TRACKS AND FROM BOTH DIRECTIONS

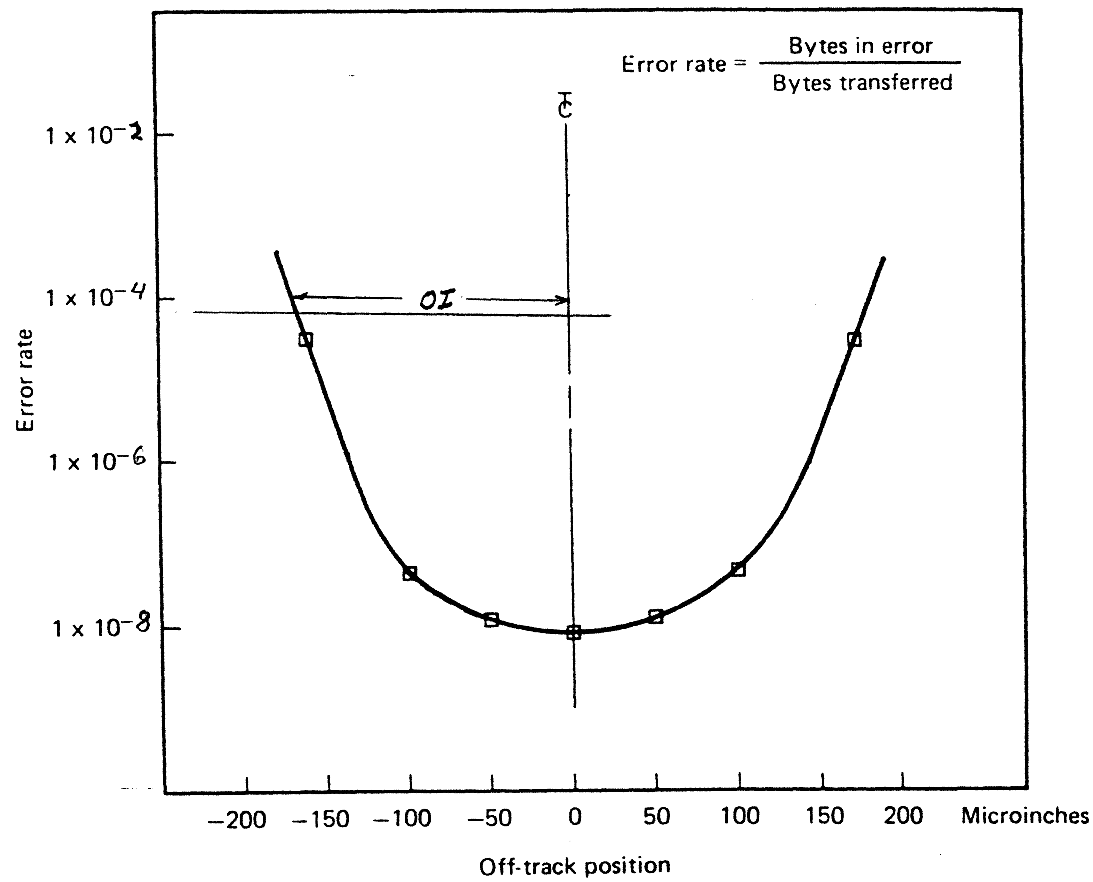
WHY IS THERE A HUMP IN 747 CURVE?



BATHTUB CURVE

- THE BATHTUB CURVE IS ONE OF THE TESTS USED TO DETERMINE THE TOTAL SOFT ERROR RATE. IT GIVES THE ERROR RATE AS A FUNCTION OF THE OFF-TRACK POSITION OF THE READING HEAD.

- IT IS RUN LIKE THE OI TEST EXCEPT THAT AT EACH POINT OFF-TRACK ENOUGH DATA IS COLLECTED TO DETERMINE AN ERROR RATE I.E. (BYTES IN ERROR)/(BYTES READ)



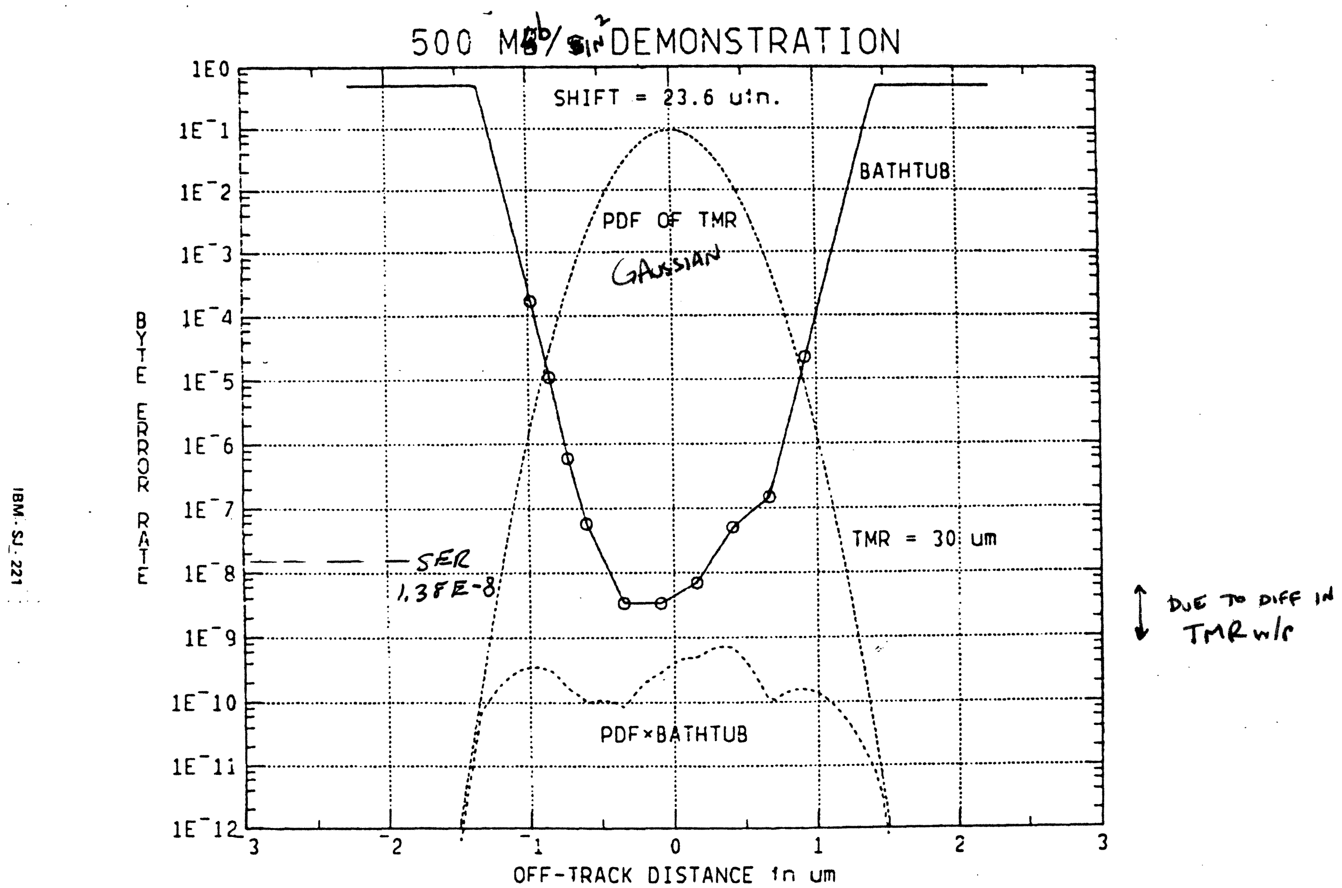
- THE CURVE MAY OR MAY NOT INCLUDE THE ON TRACK POINT. FOR A GOOD SYSTEM THE ON TRACK ERROR RATE MAY BE AS LOW AS E-8 OR E-9 AND MAY TAKE MORE THAN ONE DAY TO MEASURE ACCURATELY. OFTEN TIMES IT IS ONLY ESTIMATED BY EXTRAPOLATION.

- THE OI IS THE OFF-TRACK DISTACNE AT THE APPROPRIATE ERROR RATE.

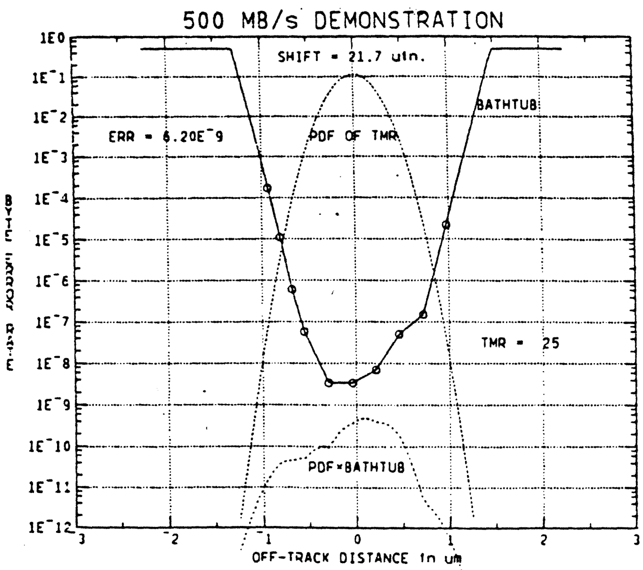
- ALL ERROR RATE TESTS ARE A FUNCTION OF THE DATA PATTERN USE FOR THE DATA TRACK AND FOR THE OI TRACKS. OFTEN A LOW FREQUENCY IS USED FOR THE OI TRACKS. THUS ONE MUST BE CONSITANT WHEN COMPARING ERROR RATE INFORMATION ESPECIALLY FROM DIFFERENT TEST STANDS.

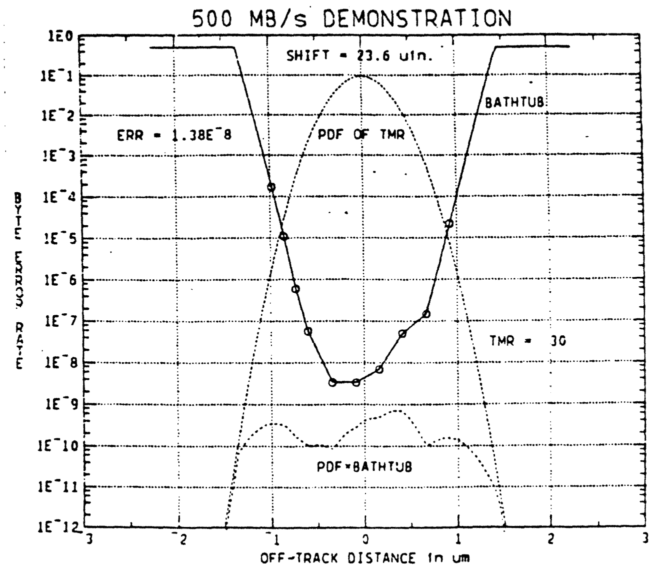
TMRw/r AND SOFT ERROR RATE

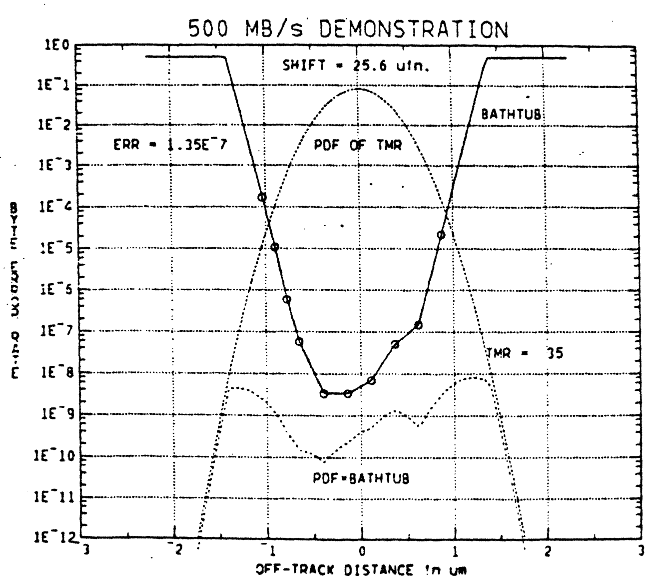
- THE BATHTUB CURVE GIVES THE ERROR RATE AT EACH LOCATION OFF-TRACK.
- TMRw/r PROBABILITY DENSITY FUNDTION (PDF) IS THE PROBABILITY OF BEING AT EACH LOCATION OFF-TRACK. THE WIDTH OF THE PDF IS RELATED TO THE 3 SIGMA VALUE OF THE TMR.
- THE POINT BY POINT PRODUCT OF THE BATHTUB AND PDF GIVES THE EXPECTED ERROR AT EACH LOCATION OFF-TRACK.
- THE INTEGRAL UNDER THE PRODUCT CURVE GIVES AN EXPECTED SOFT ERROR RATE (SER) FOR THIS COMBINATION.

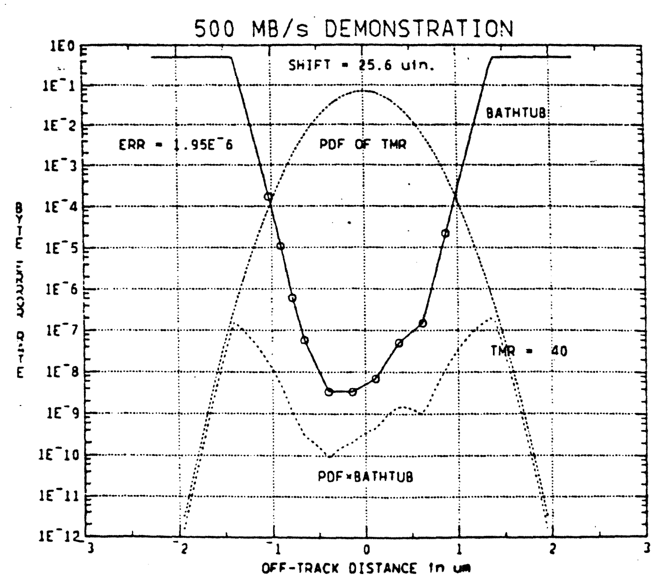


- THIS SOFT ERROR RATE CHANGES WITH THE TMR 3 SIGMA VALUE AS DOES THE SHAPE OF THE PRODUCT CURVE.









HIGHER PROBABILITY OF BEING WAY OFF TRACK

- FOR THE TMR = 25 μIN CASE THE ERROR RATE IS DOMINATED BY ON TRACK ERRORS. IN THIS CASE THE ERROR RATE COULD BE DECREASED BY USING A WIDER HEAD.

- FOR THE TMR = 40 μIN CASE THE ERROR RATE IS DOMINATED BY OFF-TRACK ERRORS. IN THIS CASE THE ERROR RATE COULD BE DECRASED BY USING A NARROWER HEAD.

- OPITIMIZATION OF HEAD WIDTH

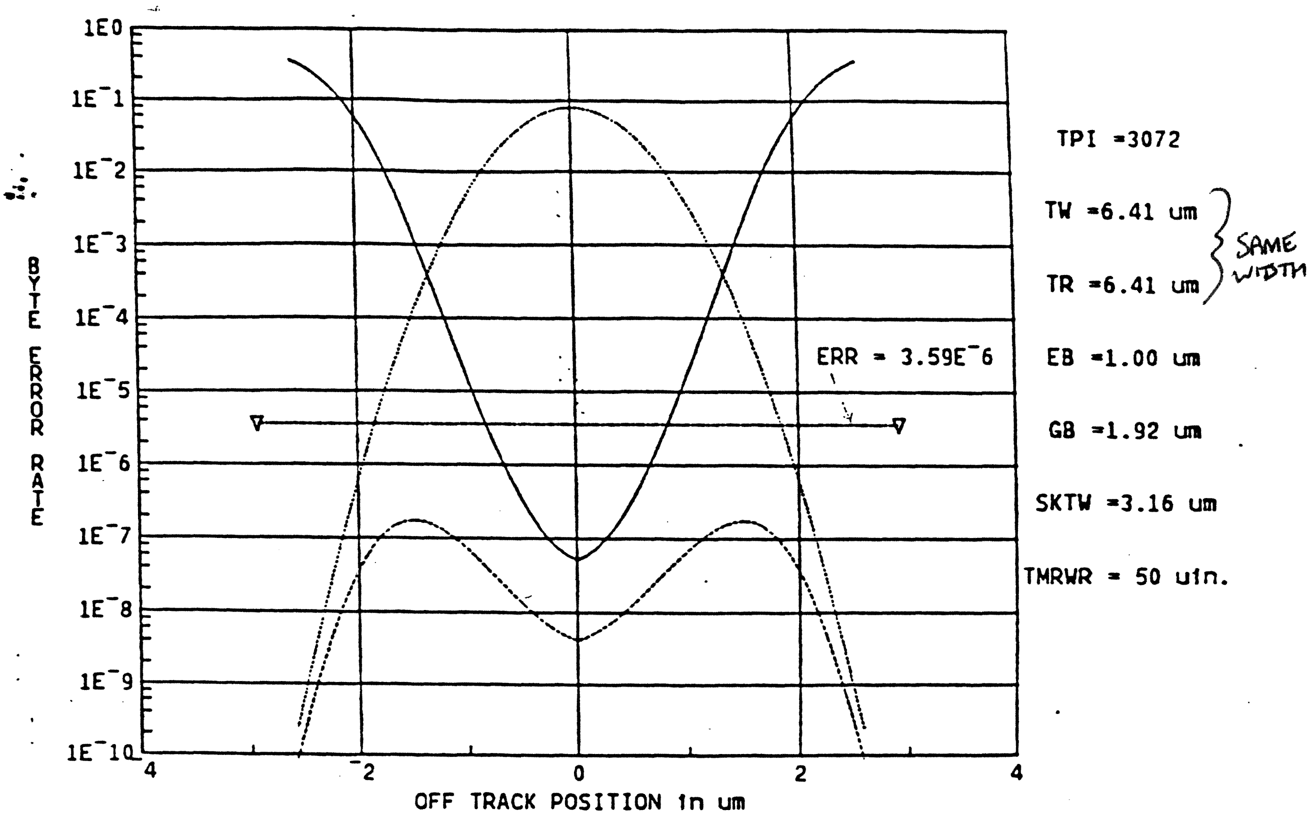
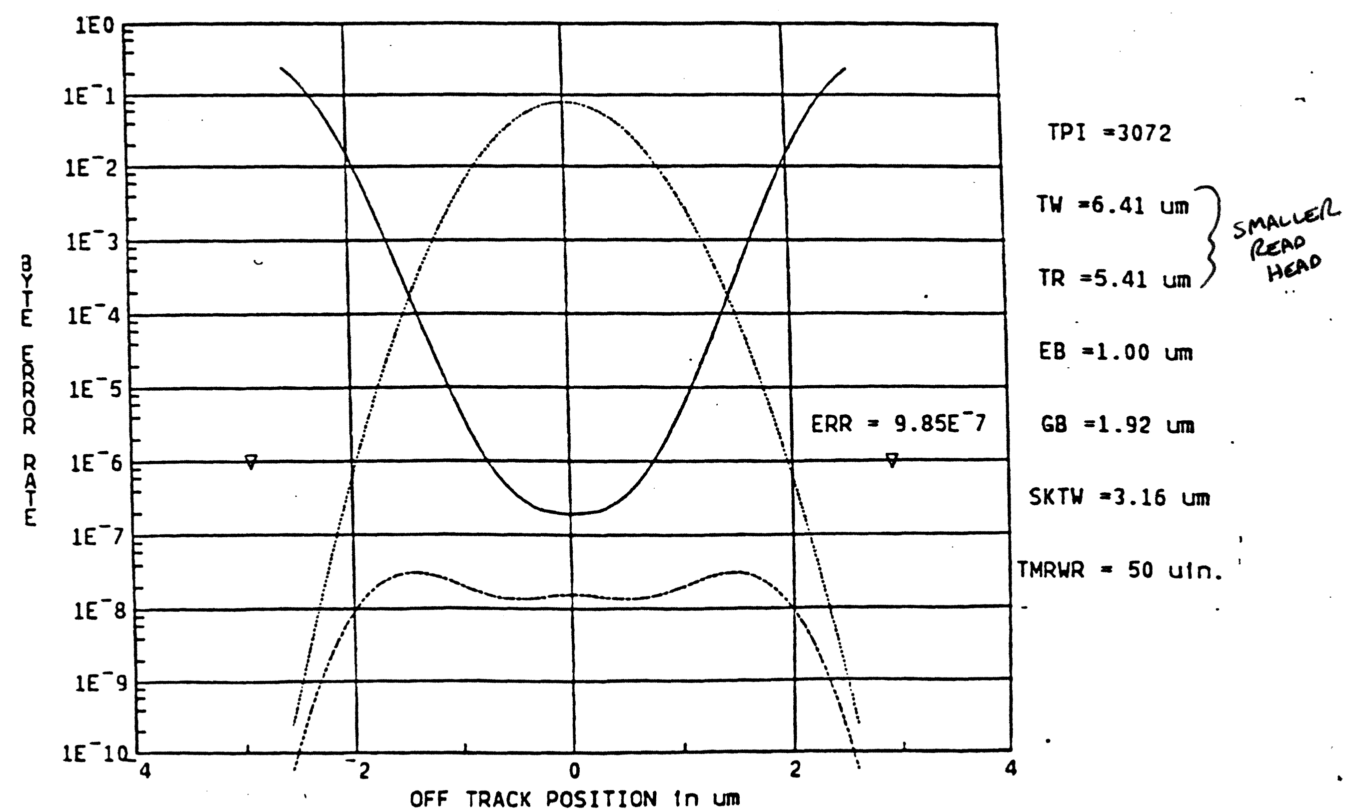


Figure 19



THE SQUEEZE CURVE AND TOTAL SER ASSCESSMENT

- THE SER AS OBTAINED FROM THE BATHTUB AND TMRw/r IS ONLY PART OF THE ERROR RATE PICTURE. THE IMPACT OF ADJACENT TRACK SQUEEZE AND THE TMRw/w IS OBTAINED FROM THE SQUEEZE CURVE

- THE SQUEEZE CURVE IS GENERATED BY A RUNNING SERIES OF BATHTUB CURVES FOR AS A FUNCTION OF AN ADJACENT TRACK POSTION MUCH LIKE THE 747 TEST EXCEPT WITH A BATHTUB CURVE RUN AT EACH POSITION.

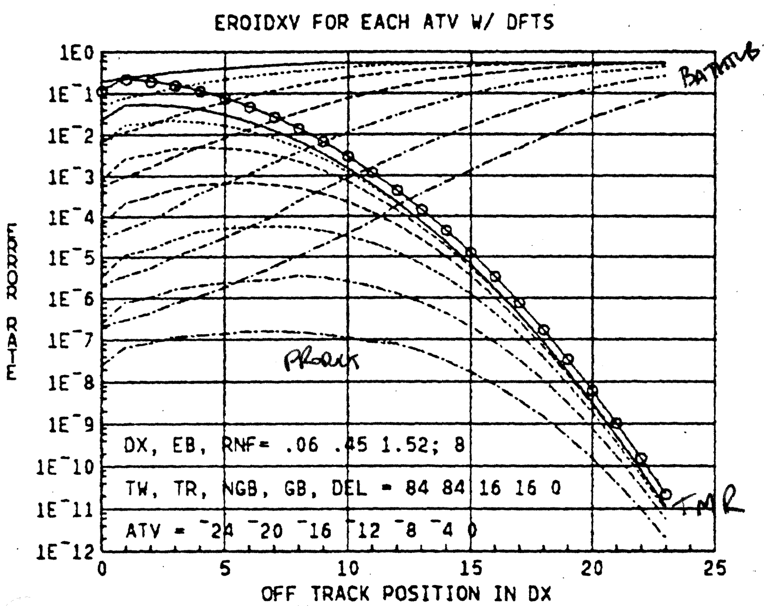
- AN EXPECTED ERROR RATE FOR EACH BATHTUB AND A GIVEN TMRw/r IS CALULATED AND PLOTTED AS A FUNCTION OF THE ADJACENT TRACK PITCH.

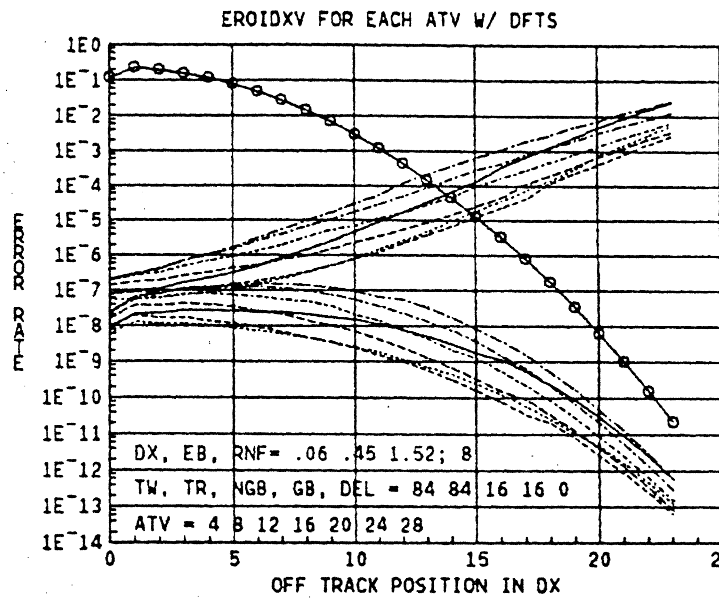
- THE PDF OF THE TMRw/w IS THEN PLACED AT THE TRACK PITCH CORRESPONDING TO A TRACK DENSITY TO BE EVALUATED.

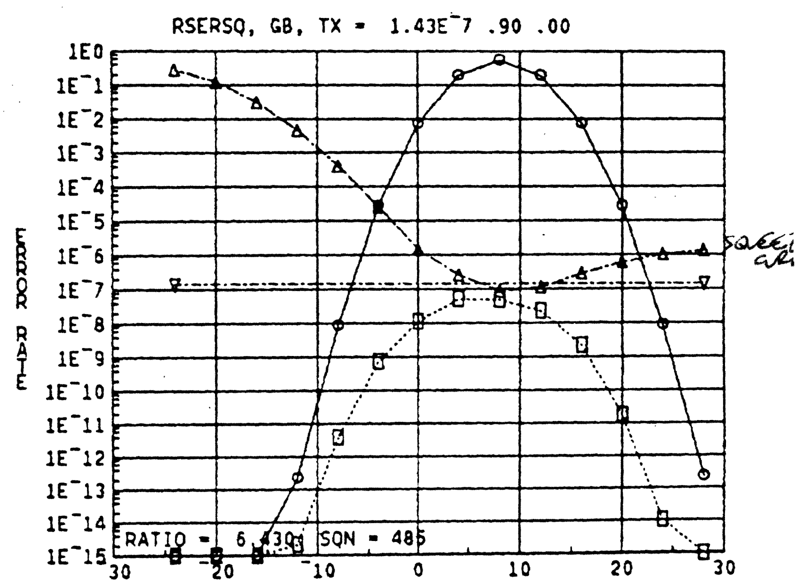
- THE INTEGRAL OF THE PRODUCT OF THE TMRw/w PDF AND THE SQUEEZE CURVE IS THE TOTAL SOFT ERROR RATE.

- IF THE ERROR RATE IS HIGHER THAN EXPECTED EITHER THE TMR´S HAVE TO BE REDUCED OR THE TRACK PITCH INCRASED (TPI DECREASED)

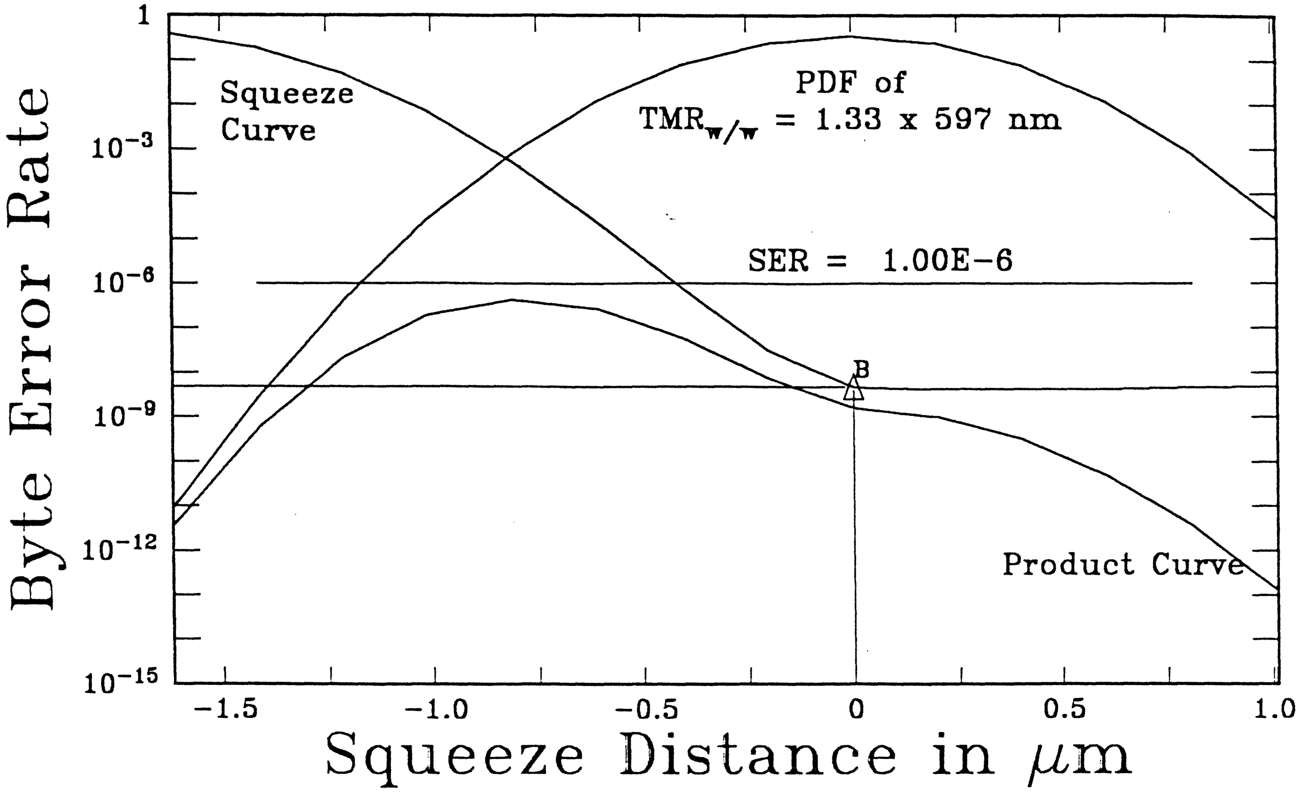
- GENERATION OF SQUEEZE CURVE

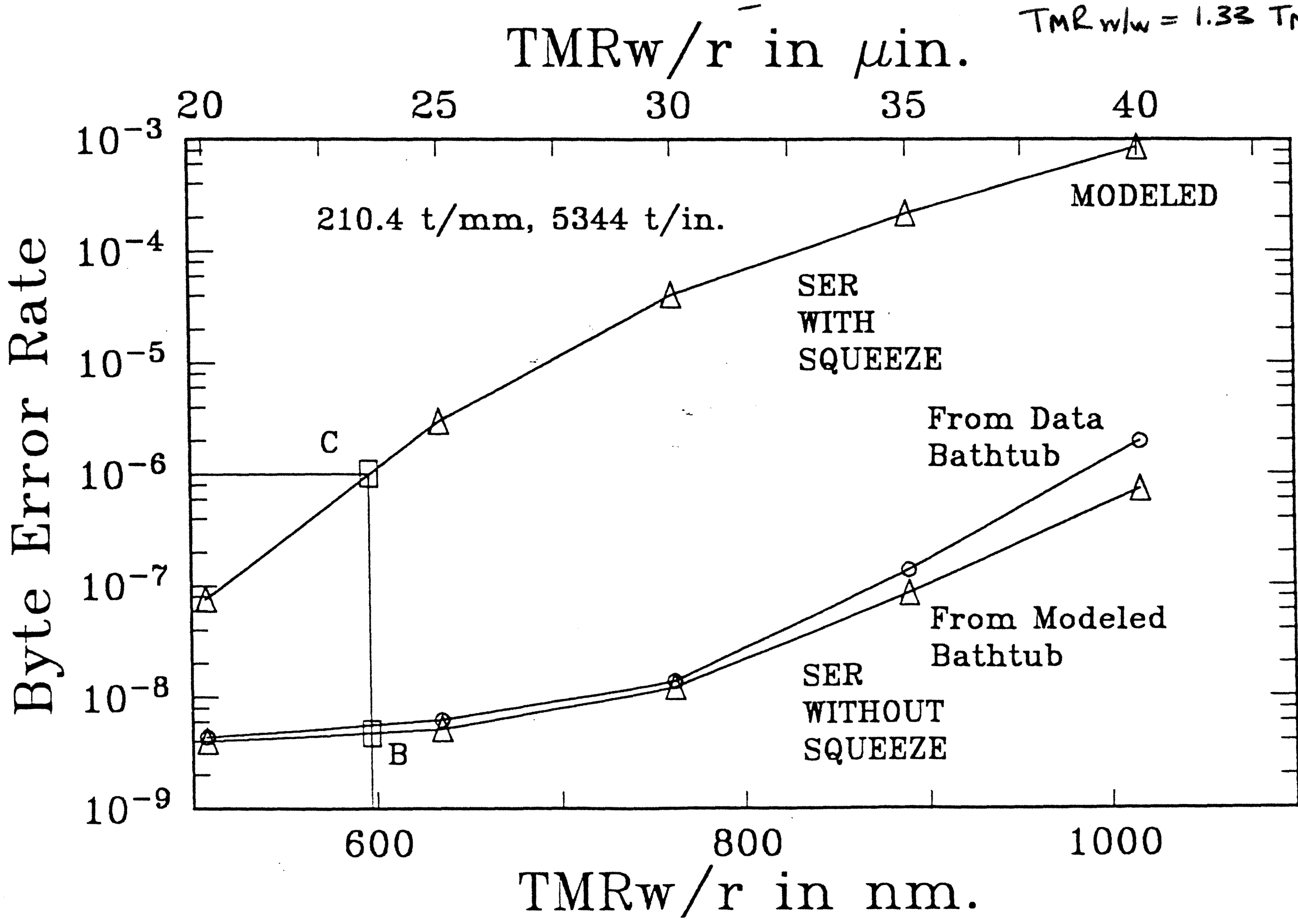






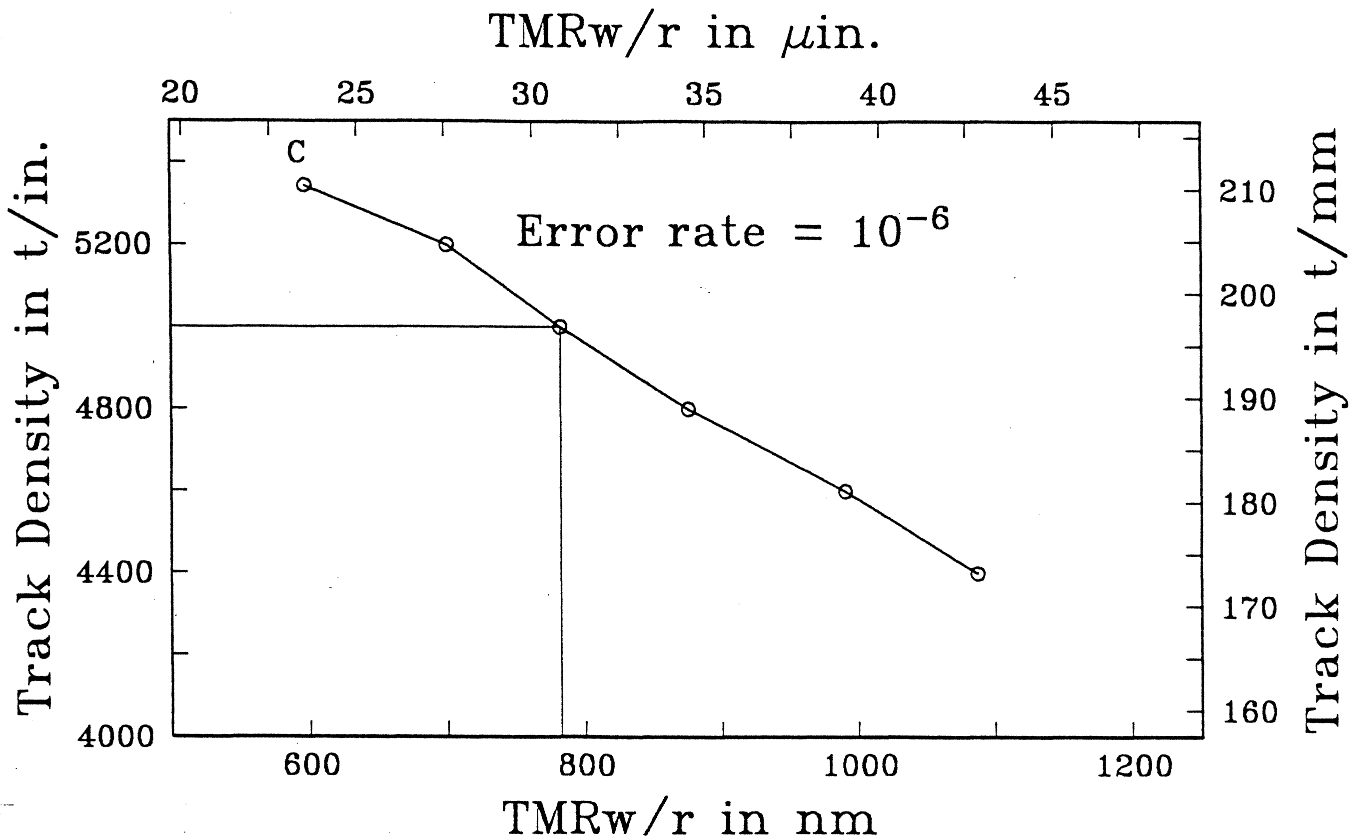
- SHOWN BELOW IS THE SQUEEZE CURVE AND A PLOT OF SOFT ERROR RATES FOR THE 500 MILLION BIT/IN² DOMONSTRATION AS A FUCTION OF TMR FOR A TPI OF 5344.





$TMR_{w/w} = 1.33\ TMR_{w/r}$

- SHOWN BELOW IS A PLOT OF TPI VS TMR FOR THE 500 MILLION BIT/IN^2 DEMONSTRATION.



- FOR THIS AND THE PREVIOUS 2 CURVES THE HEAD WIDTHS WERE FIXED. FOR A DESIGN THEY SHOULD BE OPTIMIZED FOR EACH TMR AND TPI.

PROBLEM 13.1

For a head disk assembly TMRr/w IS 80 μ inches and TMRw/w IS 105 μ inches. THE OI measurement is 110 μin and TPF is 450 μIN. Assume $K_1 = K_2 = 1.3$. Find all parameters of the lambda curve and plot it. Find the minimum allowable pitch.

DEMONSTRATION OF 500 MEGABITS PER SQUARE INCH WITH DIGITAL MAGNETIC RECORDING

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Oral Paper EC-07

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Abstract - **This paper describes the testing and modeling methods undertaken to demonstrate and verify an areal density of 500 million bits/in.^{2} with a combined inductive, thin film write head and a magneto-resistive read head on an advanced, state of the art thin film disk. The linear density was 100,000 bits/in. (3937 bits/mm), the track density was 5,000 tracks/in. (196.9 tracks/mm) and the flying height was 2.5 μin. (64 nm).**

INTRODUCTION

The IBM Magnetic Recording Institute set an objective to demonstrate an areal density of 500 million bits/in^2 (3937 bits/ mm^2), in an environment where the most aggressive products were just approaching 100 million bits/in^2. The criteria for success were set as: a flying height of 64 nm (2.5 μin.), with a 3σ write-to-read track misregistration (TMRw/r), including read-write misalignment, of no less than 760 nm (30 μin.) and a total raw soft error rate (SER) of 10^{-6} (errors/byte). The flying height and TMRw/r criteria were selected as obtainable mid-nineties product objectives. This paper describes the characterizations of the head, disk and channel, the linear and track density measurements, and the test and modeling methodologies used to verify the soft error rate and TMRw/r for the measurements made.

COMPONENT CHARACTERIZATIONS

The narrow track recording head was a combination of a thin-film inductive write element and a magnetoresistive read element. The read head was similar to the type described in paper[1]. The head gap was .4 μm and the element width was 3.6 μm. The recording was done on a CoPtCr thin-film disk, similar to the type described in paper[2], but with a coercivity of 1335 Oe and remanence-thickness product of $.8\times10^{-3}$ emu/cm^2. Many of the geometric and magnetic target values for the head and disk were set by use of modeling techniques described below. The following were used to gain our objectives: a peak detection channel with a data rate of 4.5 megabytes per seconds (MB/s), a second derivative equalization boost of 10 dB at 17.5 MHz, a five-pole low-pass filter with a 3 dB attenuation at 22 MHz and a (1,7) run length limited encoding scheme. The magnetic head-disk separation was approximately 102 nm (4 μin.) with a flying height of 64 nm. The difference was split between head recession and disk overcoat. The head output at low density was 643 $\mu V_{p\text{-}p}$ with a 3 dB roll-off point at 2400 flux changes per mm (fc/mm). Figure 1 shows both unequalized and equalized isolated pulses. Figure 2 shows the micro-track profile of the read head. The low frequency track profile of the written track was very uniform, had fairly steep sides and the width was 4.3 μm. The total signal to noise ratio was 28 dB, defined as base to peak isolated pulse divided by rms noise. The disk noise was measured with high density data present.

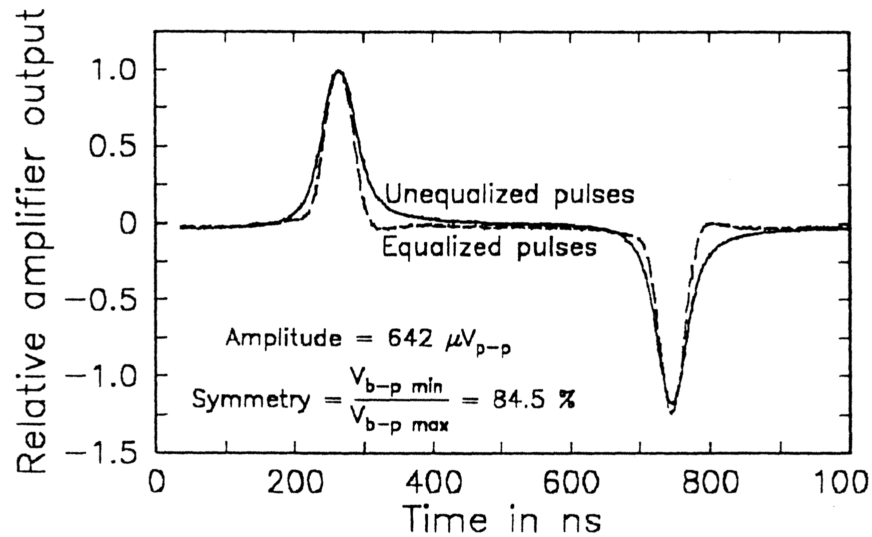

Figure 1. Normalized, equalized and unequalized isolated pulses.

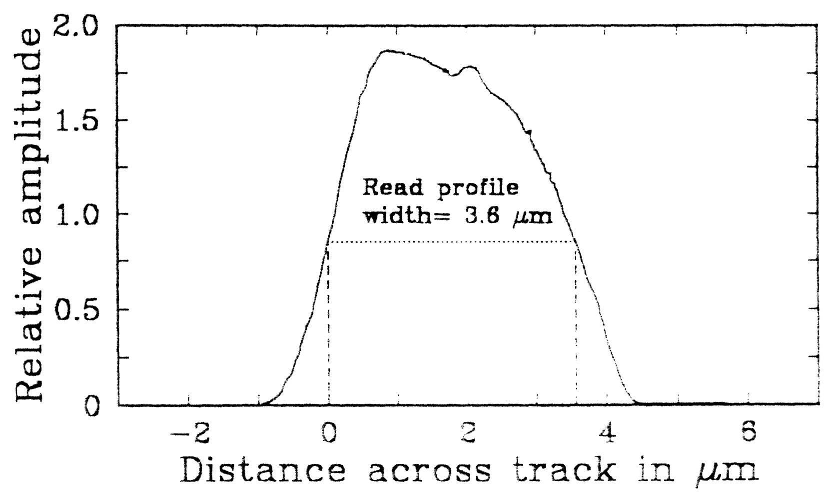

Figure 2. Read head micro-track profile using a .5 μm written track width.

SELECTION OF LINEAR AND TRACK DENSITIES

To determine the linear and track densities and the required TMRw/r for the desired soft error rate, a combination of off-track tests and modeling was used. Many of the test procedures described were developed in IBM the mid seventies

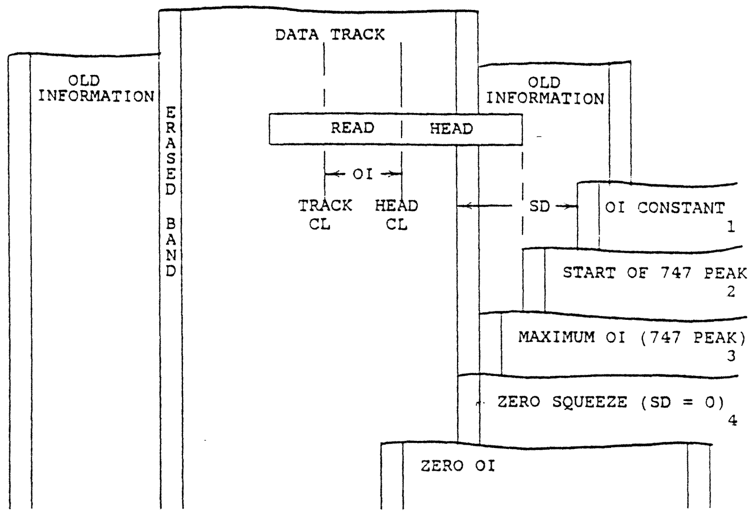

Figure 3. Old information and 747 curve test schematics. SD is the squeeze distance, OI the old information distance. Numbers on the left refer to points in Figure 4.

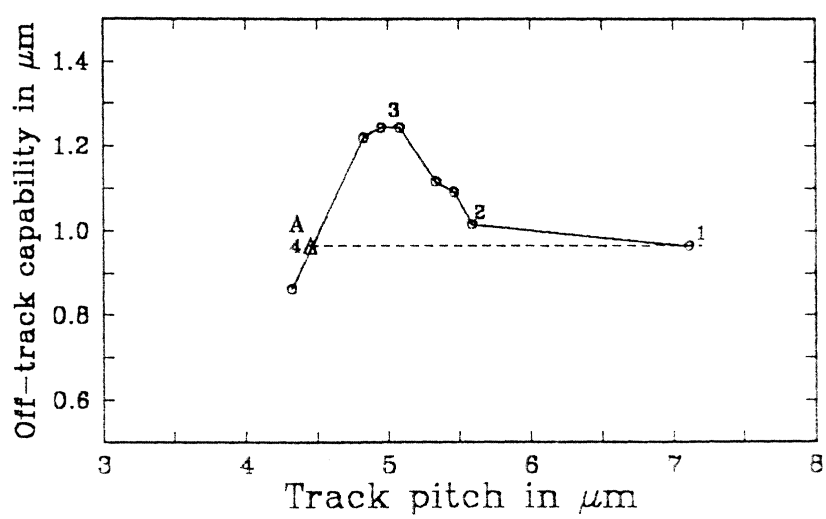

Figure 4. 747 curve for 500 Mb/in². Point A occurs when the erased bands of the adjacent and center tracks overlap. Numbers refer to Figure 3.

These tests measure performance, expressed as error rates, under all off-track combinations of the head during reading and writing. The Track Density Error Rate Model, developed by Joost Mortelmans, simulates these tests by using as input some 20 geometric and magnetic component parameters. and calculates the SER from the signal to Gaussian noise ratio (SNR) [3] and the amount of signal type noise from adjacent tracks. This enables the model to compute the total SER as a function of assumed TMRw/r and the write-to-write track misregistration (TMRw/w).

The first step was to determine the approximate track density capability of the test head by generating a 747 curve (so named for its resemblence to the front of a 747 airplane). This test consists of finding the off-track capability when a track of random data is centered at the boundary of two previously written tracks and an adjacent track is written at a variable distance. Figure 3 shows the basic background pattern with the approaching adjacent track in the lower half. It also shows the presence of erased bands at the edge of each recorded tracks. For a given track pitch, the head is moved off-track in small increments until all written sectors have failed three times in 30 read operations. The mean of the resulting histogram of failed sectors versus off-track distance is called OI and this corresponds to a byte error rate of about 8×10^{-5}. Figure 4 shows OI versus adjacent track pitch for the 500 MB/in.^{2} components. Referring again to Figure 3, when the adjacent track is far removed from the center track, it will have no impact on OI which will remain constant. However, as the old information band, between the data and the squeezing tracks becomes smaller, the off-track capability will increase and reach a maximum when the two erased bands abut. Further squeezing will result in a decrease of OI and lead to a position where the two erased bands overlap; this is point A in Figure 4, where OI is the same as the initial point where the adjacent track is far removed from the center track. For yet smaller track pitches, the adjacent track erases or overwrites the center track, which causes OI to decrease precipitously. The track density at which the 747 curve peaks is close to the optimum for that head. Figure 4 shows this peak in the vincinity of 5 μm (200 μin.) or 5000 t/in.

The second step was to determine the linear density to use for tests involving large quantities of data. This was accomplished by running the old information test as a function of linear density. This test also measures off-track capability and consists only of the intial step of the 747 procedure; no adjacent track is recorded. Figure 5 indicates OI as a function of linear density. Three trials were run at three different equalizer and detector clip level settings.

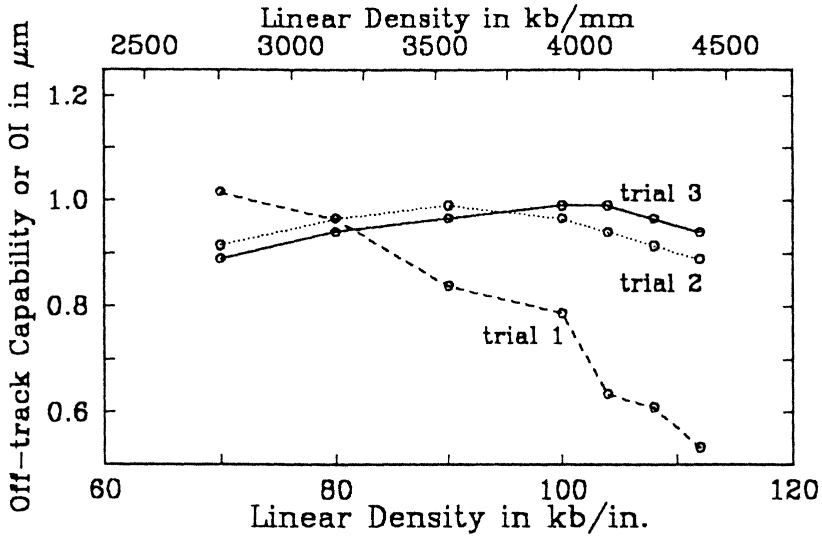

Figure 5. OI or off-track capability versus linear density for three settings of the equalizer and the detector clip level, using the OI test.

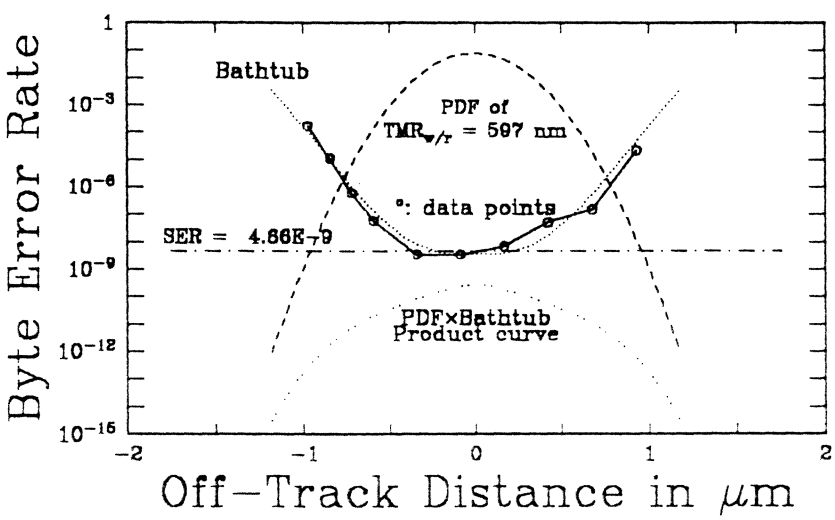

Figure 6. Measured and calculated bathtub, when no adjacent track is recorded. Also shown are, PDF of TMRw/r, the product curve and its integral value (horizontal line) which yields the expected error rate and point B in Figures 7 and 8.

Since the 747 curve showed that our track density would be close to 5000 t/in and since our goal was 500 Mb/in.², we selected 100 kbpi with the settings of trial #3 for the testing of large quantities of data.

SER AND TMR TEST AND MODELING RESULTS

The solid line bathtub curve, shown in Figure 6, was obtained by measuring the error rate as a function of off-track position of the read head, while collecting in excess of 10^9 bytes of data from 20 tracks in an overnight test run. The track configuration is that of the OI test geometry, which is equivalent to a separation between center and adjacent tracks of one erased band width. In this case SD of Figure 3 equals 0 which corresponds to 5344 t/in. We initially screened the tracks at a 65% defect clipping level to identify the sectors to be skipped, however, no skips were required. The track density for the desired SER was determined as a function of TMRw/r and TMRw/w. The latter was assumed to be 33% larger than the former. The track density analysis consists of two steps, one for the write-to-read and one for the write-to- write TMR.

In the first step, a bathtub curve is calculated (smooth curve in Figure 6) for the same track geometry as described in the test procedure to obtain the data bathtub. Minor adjustments, within the uncertainty of the parameters, were made for a better match to the data.

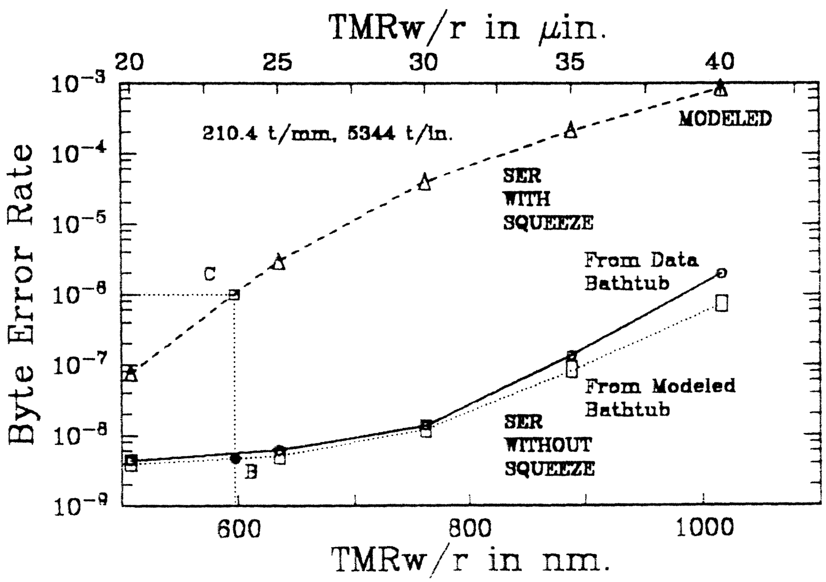

Figure 7. Overall SER with squeeze (top) and SER from data and calculated bathtub without squeeze.

An expected error rate value was obtained by integrating the product of the bathtub and the (Gaussian) probability density function (PDF) of the assumed TMRw/r. The width of the PDF relates to the 3σ value of the TMRw/r which is equal to 597 nm (23.5 μin.). This error rate is point B in Figures 7 and 8. Similarly, for each other value of TMRw/r, the bathtubs will correspondingly yield expected error rates which are plotted in the lower part of Figure 7 as the dotted curve. The solid curve results from using the data bathtub of Figure 6.

In the second step, both TMRs are kept constant and a series of bathtubs are calculated as a function of adjacent track distance. The expected error rates of the bathubs and the fixed TMRw/r yield the squeeze curve shown in Figure 8. Also shown are the PDF of the TMRw/w, the product curve and its integral, the overall error rate. This PDF of the TMRw/w is centered at a squeeze distance of SD = 0, which corresponds to the OI test geometry and to 5344 t/in. (210.4 t/mm). This track density is very high and also results in a high error rate as shown in Figure 8. The left hump of the product curve corresponds to the over-writing of the center track by the adjacent track (TMRw/w), while the right hump, which is suppressed here because of the close proximity of the adjacent track, corresponds to the amount of old information between the two erased bands. At the optimum track density of the components, the two humps would have equal heights, indicating a balance between too high and too low a track density.

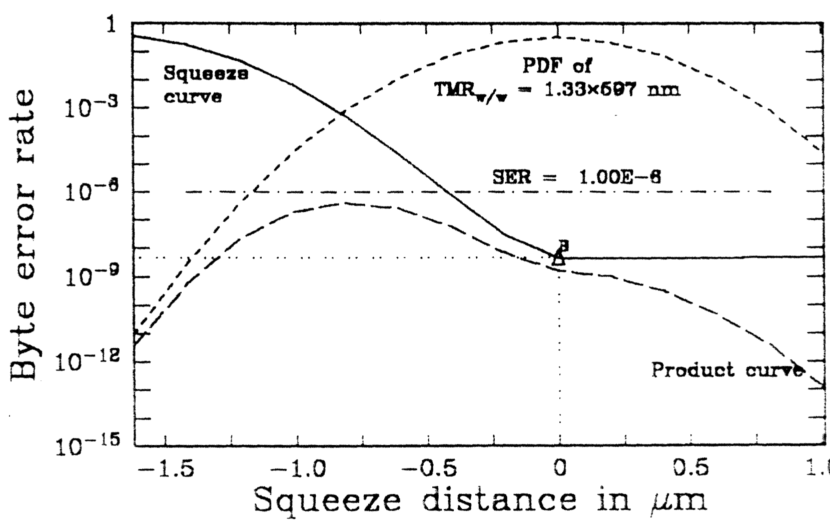

Figure 8. Calculated squeeze, PDF of TMRw/w, the product curve and its integral value which yields the overall expected error rate.

This calculation was repeated for a range of TMRw/w values to obtain the upper curve, in Figure 7. The SER value at 10^{-6} is point C, also shown on Figures 8 and 9.

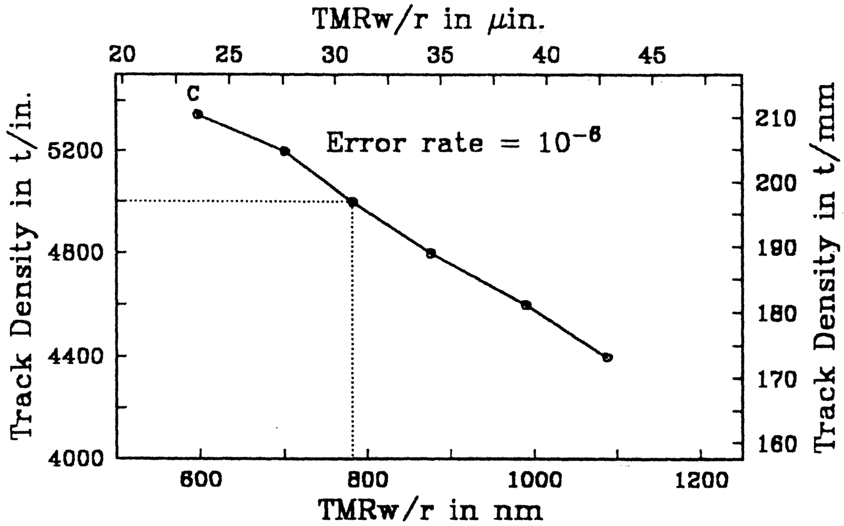

Figure 9. Track density versus TMRw/r at a SER of 10^{-6}

The total process of Figure 7 is repeated at different nominal track densities to generate Figure 9 which is a plot of the track density versus TMRw/r for a total soft error rate of 10^{-6} (byte). TMRw/r for 5000 t/in. (210.4 t/in.) is 30.8 μin.(772 nm), which met the TMR objective of not less than 30 μin.(760 nm).

CONCLUSION

We have demonstrated longitudinal magnetic recording and playback at 100 kb/in. (3937 b/mm) and 5000 t/in. (196.9 t/mm) equivalent to an areal density of 500 Mb/in.^{2}. The components were characterized in great detail including write, read, erased band and read profile skirt widths. A combination of off-track measurements and the Track Density Error Rate Model showed that the target density was obtained for a soft error rate of 10^{-6} and a TMRw/r of 30.8 μin. (782 nm). Although this was accomplished in a laboratory environment, the capability of magnetic components to record and read back at these high linear and track densities was clearly demonstrated. Incorporation of these densities into a product with the associated flying height and TMRs still represents significant engineering challenges.