# HIGH-DENSITY MAGNETIC HEAD DESIGN FOR NONCONTACT RECORDING

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Summary -- The information storage density in digital magnetic recording is dependent on both the pulse resolution and the track definition. This paper is concerned with these two factors in the design of magnetic heads for noncontact recording.[1] A concept of changed pole-tip geometry which led to a significant improvement of pulse resolution is introduced. A general expression based on "single-pulse" superposition is derived for various bit densities and data codes. In addition, several recording methods are discussed for achieving near-maximum track density under various head-repositioning error conditions. As shown, high-density heads for noncontact recording have been designed successfully by applying the concept and techniques developed. Good correlation has been realized between analytical and experimental results. Performance characteristics under simulated machine conditions are presented.

## INTRODUCTION

One of the most fundamental motivations in magnetic recording as applied to information storage is to achieve increasingly higher storage densities. Since the storage density per unit area in digital recording is the product of the longitudinal bit density and of the transverse track density, the information storage potential is dependent on both the pulse resolution and the track definition. These two factors are of primary concern in the design of high-density magnetic heads. In contact recording, magnetic heads for digital recording have been demonstrated, within the laboratory environment, for a pulse resolution of up to 2,000 BPI (bits per inch) and a track definition of 500 TPI (tracks per inch).[2]

In noncontact recording, techniques are not available for achieving densities higher than 1,000 BPI and 100 TPI,[3] with satisfactory system operation. This paper discusses the approaches to these two major problems. To attain higher pulse resolution, the concept of controlling the writing field distribution is applied. To achieve better track definition, an intertrack shield and a well-chosen recording method for a given head-repositioning error are suggested.

The semi-infinite pole shape is most commonly used in a longitudinal-recording head (ring-type structure). This form of pole face operates quite satisfactorily on tapes, and attains high bit density in contact recording. In noncontact recording, however, its resolution suffers seriously as a result of the increased head-to-medium (H-to-M) separation. That is, the field gradient is steep near the pole face but becomes more gradual as the distance from the pole face increases. The field distribution of the write head and the sensitivity function or weighting function (a function giving the sensitivity of the reading coil to the surface magnetization) of the read head can be controlled by changing the geometry of the pole tip. Heads based on this concept of control through changed pole tip geometry have been designed, and significant improvement in pulse resolution has been achieved.

When the bit density is higher than a figure equal to the reciprocal of the pulse width (transition region), the readback pulse form changes due to partial modification by the adjacent pulse. An equation based on "single-pulse" superposition has been derived for predicting the readback signal for various bit densities and data codes.

Mechanical limitations and tolerances under actual machine conditions make head repositioning a major problem in magnetic recording. When a read head is displaced from a given written track, two undesirable effects normally result. One is the drop in the readback signal amplitude; the other is the noise picked up from residual magnetism outside the recorded track and from crosstalk from adjacent tracks. This paper presents several methods commonly employed to achieve near-maximum track density and to minimize the undesirable effects; it also discusses the design analysis and consideration of these methods.

No attempt is made to discuss the frequency-dependent factors, such as the head frequency response, read amplifier response, write current rise and fall times, etc. The primary concern in this study is the pulse widening caused by the broad field distribution in noncontact recording. Track density limitations that may arise from interhead crosstalk in a multiple-head stack are not considered, but stress is placed instead upon the limitation caused by head repositioning errors.

By applying the theory and techniques developed in connection with the IBM magnetic disk storage development program, practical high-density heads for noncontact recording have been successfully designed. This paper includes test results and their correlations with the theory, and presents performance characteristics of several high-density heads.

## DESIGN ANALYSIS AND CONSIDERATIONS

### Coding Methods

Many coding methods of recording of information on a magnetic medium have been proposed. The most widely used techniques are the RZ (return-to-zero), NRZ (non-return-to-zero), and PM (phase modulation). Each method has its advantages and disadvantages. Various modifications and different detection techniques have been successfully employed to increase information density. However, the bit density achievable by any method is determined by the basic resolution of the written transition of magnetization reversal and the steepness of the head-sensitivity function. Thus the maximum packing density is a function of the actual width and quality of an isolated readback pulse. The NRZI (non-return-to-zero, IBM code) method of recording was used throughout the study presented in this paper, and an isolated NRZI pulse was employed for analyzing the factors which influence its width and quality in noncontact recording.

### Head-to-Medium Separation

Besides meeting the electrical circuit requirements on information storage density, bit rate, signal amplitude, noise level, phase shift, and track density, the magnetic head for a given application must function reliably within the mechanical tolerances imposed by the system. These tolerances include possible variation in head-to-medium separation, change in relative head-medium motion, head repositioning error, physical size, etc.

The major design problems of the heads for high information storage density are good pulse resolution and fine track definition. These problems become more difficult with increasing head-to-medium separation.

Pulse resolution is a function of head-to-medium separation. The greater the distance from the head gap, the more gradual the field gradient becomes. Consequently, if the recording medium is excessively distant from the write head, it is subjected to a field with a much decreased gradient. Fig. 1 shows the field distribution near the surface and at some distance above the pole face. The more gradual this gradient gets, the longer becomes the transition region of magnetization reversal along the recording medium. This effect will result in poor pulse resolution.

Fringing of the write field causes the width of the written track to be somewhat larger than the physical width of the write pole tip. In saturation-type recording, the written track width becomes wider for thicker recording media and for larger head-to-medium separations. However, the amount of increase in the written track width caused by the fringing field is independent of the physical size of the pole tip width; for this reason the increased track width from fringing is a larger percentage of the total track width for the narrower tracks.[2]

### Write Head Geometry

The conventional pole tip geometry of the head used for longitudinal recording is usually semi-infinite. This shape of pole face is quite satisfactory for contact recording. For noncontact recording, however, the bit density that can be achieved is limited. The write field of the head is assumed to be composed of longitudinal and perpendicular (horizontal and vertical) components,[4] (Fig. 1). The magnitude of this field at a given point is of importance, as it determines the remanence of magnetization of the particles in the recording medium. However, the trailing field is of utmost concern, because the final effect upon the medium is essentially that exerted by the trailing pole, since the influence of the leading pole will be modified by the trailing field.

When a particle passes the gap, it is magnetized in one polarity. If the write field changes its polarity before this particle has passed completely out of the influence of the reversed field, it is partially magnetized in a reversed polarity to a varying degree dependent on the gradient across the head.[5] This condition results in partially demagnetizing the recorded medium which is still within the field of the head as it changes polarity. Consequently, the pulse resolution is limited in noncontact recording, by a semi-infinite pole face, where the field gradient is very gradual at some distance from the head. To attain high pulse resolution, the write trailing field effect must be eliminated or reduced to a very minimum. This calls for a steep gradient at the trailing edge of the gap. Fig. 1 shows that the field gradient is very poor at some distance above the pole face of a semi-infinite pole tip head.

Accurate presentation of the field pattern is extremely difficult because of the nonlinear relationship and asymmetrical nature of the magnetic cycle. The models given here are highly simplified. However, they do explain qualitatively the effects of the pole-tip geometry in the writing and reading processes.

This paper does not consider the effects of the head gap length, of recording medium characteristics, and of thickness; these parameters have already been well treated by previous papers.[5,7] The primary interest in this study is to investigate the effect of the pole-tip configuration of a ring-type-structure head on the readback pulse resolution in longitudinal recording.

The field distribution of the head can be controlled to a large extent by changing the geometry of the pole tip. Figure 2 shows the pulse width (at the level that is 10% of the peak) as a function of the pole-tip length (L). Data was obtained experimentally with the same head for both writing and reading. That is, the pole-tip length was increased by lapping the head surface between each set of write-read data taken. Three different head-medium relative velocities were taken, but the same head-to-medium separation was maintained. Figure 3 shows the pulse width as a function of the angle $\theta$ which the edge of the head pole tip makes with the recording surface. The same head (with its angle $\theta$ changed after each step, by machining the pole-tip edges) was used in taking the data throughout the test, and the pole-tip length was maintained at approximately one milli-inch. These curves indicate that, in noncontact recording, the pulse width widens as L increases and $\theta$ decreases. The pole-tip geometry approaches closer to semi-infinite as $\theta$ becomes smaller. Consequently, decreasing $\theta$ has a similar effect to that caused by increasing L. In writing, as L increases and/or $\theta$ decreases, the trailing field effect increases, resulting in a wider transition region of magnetization reversal. In reading, as L increases and/or $\theta$ decreases, the head sensitivity function becomes more gradual, which results in a wider readback pulse.

## Read Head Geometry

Since for most practical purposes the readback pulse form can be assumed to resemble the field distribution function of the head,[6] it is apparent from Fig. 1 that the resolution in the reading process becomes poor when the head-to-medium separation gets large.

The oscillograms in Fig. 4 show the effects of the pole-tip length on both the writing and reading processes. The pulse width at the 10% (of peak) level is: in (a) 3.0 microseconds, in (b) 5.7 microseconds, in (c) 10.5 microseconds and (d) 6.0 microseconds. Both heads L-1 and L-8 are of the same design and have the same gap length. The only difference is in the pole tip length. (Head L-1 = 1.0 milli-inch, and L-8 = 8.4 milli-inches). They were tested on the same recording medium (0.43 milli-inch $\gamma\ Fe_2O_3$), at the same velocity (1000 IPS) and at the same head-to-medium separation (0.25 milli-inch). The sensitivity function of head L-1 should be the same in scanning over either transition region of magnetization reversal: That written by head L-1 and that written by head L-8. The pulse- width difference in (a) and (d) is primarily due to the difference in the widths of these two transition regions. By comparing the pulse widths in (a) and (d), it is apparent that in noncontact recording a wider transition region is written by a head with larger L. The transition region after being written, remains practically the same width regardless of which head is used for readback. Therefore, the pulse width difference shown between (a) and (b) and that shown between (c) and (d) must be due to the difference of the sensitivity functions of the readback heads. These differences indicate that a head with larger L has a broader sensitivity function. This data is in good agreement with the analysis on the effects caused by the pole tip geometry.

Based on the principles of reciprocity[6], the readback process is analyzed, and the voltage e(x) produced in the reading coil is approximated by a convolution integral of the form:

$$e(x_1)=vN\frac{d\phi}{dx_1}=KvN\int_{-\infty}^{+\infty}H(x)\,\frac{\partial M(x-x_1)}{\partial x_1}\,dx \qquad (1)$$

where $x_1 = vt$ (t=time), $\phi$ is the flux in the reading coil, K is a constant, v is the relative head-medium velocity, N is the number of turns in the readback coil, H(x) is the sensitivity function of the readback head, and $M(x-x_1)$ is the distribution of magnetization in the recording medium.

In longitudinal recording by a ring-type-structure head, it is reasonable to assume that the perpendicular component of the magnetization is negligible[7] and that the longitudinal component in the x direction is the only significant component of the magnetization. This means that $M_y = 0$ and $M_x = M$. For an idealized case in saturation recording, $M_x(x)$ can be considered as a step change of magnetization from $-M_s$ to

$+M_s$, as shown in Fig. 5. The induced voltage due to the step change of M(x) at $x_1$ is

$$e_1 = 2\ KvNM_s H_x\ (x_1) \qquad (2)$$

where $H_x(x)$ is the sensitivity function of the readback head which contributes to the longitudinal component of the magnetization.

According to (2), the readback pulse form, e(x), is proportional to the sensitivity function, $H_x(x)$. Since the field distribution of the head is a measure of its sensitivity function, e(x) can be considered, for most practical cases, to closely resemble the field distribution gradient.

The induced voltage due to the step change of M(x) of opposite polarity at $x_1$+d can be written as

$$e_2 = -2\ KvNM_s H_x\ (x_1+d) \qquad (3)$$

In NRZI coding, writing two "1's" would result in an approximate rectangular-function distribution of magnetization. If the space interval between the two step functions of opposite signs is d, the rectangular function of magnetization can be shown as in Fig. 5. This rectangular function is composed of a positive step at $x_1$, followed by a negative step at ($x_1$+d).

The induced voltage can be found by adding (2) and (3):

$$e(x) = e_1+e_2 = 2KvNM_s\ [H_x(x_1)-H_x(x_1+d)] \qquad (4)$$

Eq. (4) may be interpreted that the pulse form of the induced voltage at a given position relative to the read gap centerline is proportional to the relative head-medium velocity and the surface magnetization. The pulse form of the induced voltage also corresponds in time to the sensitivity function, $H_x$, at $x_1$ and at $x_1$+d. That is, in addition to the application of the principle of reciprocity, the principle of superposition is extended to the analysis of the readback pulse.

Each character is represented by one or more transitions of magnetization reversal spaced at various intervals, d, which varies according to the bit density and data code. The readback pulse form and the signal-to-noise ratio varies with the bit density and the data code. Therefore, to achieve high bit density and good signal-to-noise ratio, noise in the baseline and asymmetry on the pulse form should be eliminated or reduced to a very minimum.

The resultant signal and noise can be analyzed and predicted from a single isolated pulse. Fig. 6 (a) shows two isolated pulses ($e_s$), each of which has a preceding noise spike ($e_n$). When the interval, d, between the two data pulses gets smaller, the noise spike is superposed onto the data pulse at a spacing which is equal to that between the data pulse and the noise spike, giving a distorted pulse form as shown in Fig. 6(b) and (c). These oscillograms exhibit clearly the phenomenon of pulse superposition and give good qualitative confirmation of the foregoing analysis (Eq. (1) through (4)).

## Recording Methods

For a given system, the track density achievable depends largely upon the head-repositioning accuracy, a problem of particular importance in "random-access"-type memories. Tight mechanical tolerances and special techniques, such as automatic servo control, have been developed to minimize the head-repositioning error. The discussion of these techniques is beyond the scope of this paper. Because the head-repositioning accuracy has such important effects on the achievable track density, it cannot be neglected in the design consideration of the magnetic heads. Since mechanical tolerances always exist in any system, techniques in magnetic recording itself must be developed to attain maximum track density for a given head-repositioning error on a given system. A good comprehension of the overall system requirement and a knowledge of the mechanical tolerances imposed on the head are therefore required.

The four parameters of the head output that are of primary interest concerning reliability are the readback pulse amplitude, pulse width, peak shift, and noise level. When the detection-circuit tolerances in respect to these major parameters are known, a nearly optimum head design can be achieved, so that satisfactory and reliable performance is attained. The proper recording method for a given system is a prime consideration in attaining this performance.

Three methods of recording commonly used in digital computers are:

(1) Write and read on same track width.

(2) Erase-wide and read/write-narrow.

(3) Write-wide and read-narrow, without erasing.

Method (1) requires only one magnetic element, and the previously written data is not erased before writing. This method can be economically accomplished with one common pole tip for both writing and reading. It is generally used in tape and drum applications where the off-track head displacement is small. However, merely writing over old information without first erasing can result in several undesirable characteristics. Under certain conditions this method of recording can produce phase shift if the intensity of the write field is insufficient to completely reverse the previous magnetization or to overcome the distortion that may be caused by the previously written data. A write current equal to twice saturation is required to make the peak shift unmeasurable.[7]

For a given head-to-medium separation and on a given recording medium thickness, for most systems optimum resolution is attained at the intensity which is just sufficient to saturate the recording medium. Excessive write current tends to widen the readback pulse, reduce its amplitude and shift its peak position.[5]

Method (2) can be employed to overcome these undesirable characteristics caused by over-saturation. This method requires two separate magnetic elements: One for erasing, and the other (a somewhat narrower pole tip) for writing and reading. When the widths of the pole tips are properly designed, the residual noise and crosstalk are low. Because previously written data is first (ac or dc) erased, the write current used can be the same intensity as that of the saturation current, and the undesirable effects caused by excessive write current can be avoided. This method has a disadvantage, in that readback signal amplitude drops gradually as the head is displaced transversely across the track during reading. However, if an AGC (automatic gain control) is used in the sensing circuit, the resulting small gradual drop in signal amplitude does not seriously affect the sensing operation. The manufacturing cost of the head is low because the erase pole tip design and fabrication are simple.

Fig. 7 shows the track performance characteristic obtained by method (2). The head used was designed for 50 TPI with a total head repositioning error of 6 milli-inches. The data was taken on an iron-oxide ($\gamma Fe_2O_3$) coated disk having a coating thickness of 0.4 milli-inch. The relative head-medium velocity was maintained at 1200 inches per second, while the head-to-medium separation was 0.25 milli-inch. The readback signals of these adjacent tracks are presented in Fig. 8. As shown, partial erasure by the erase element, when the adjacent track was written at a maximum head repositioning error of 6 milli-inches, reduced the track's signal amplitude by approximately 20 per cent. Under this worst condition, however, an examination of the data indicates that noise due to old data and crosstalk is negligible, and that no peak shift is detected.

Two separate magnetic elements are also used in method (3): A wider pole tip for writing (without first erasing), and a narrower pole tip for reading. Method (3) is preferred when the head-repositioning error is large, and when constant readback signal amplitude is desired. However, both the write and read elements must be well designed and fabricated. The residual noise and crosstalk are generally higher in method (3) than in method (2). In addition, the same undesirable characteristics on the readback signal as stated in method (1) are present.

The track performance characteristic obtained by method (3) is illustrated in Fig. 9. The head used was designed for the same track density (50 TPI) and for the same head-repositioning error (6 milli-inches), and was tested under the same operating conditions shown in Fig. 7. The constant readback signal amplitude through a wide range of head displacement is attractive, but is lost when the adjacent track is rewritten at the maximum head repositioning error. (See the solid line of track C, Fig. 9.) In addition, the noise due to old data and crosstalk is somewhat higher than that attainable by method (2).

Two heads were constructed for high track-density study in noncontact recording. One was designed for 200 TPI and the other for 500 TPI. Both heads are of the dual-element type using the erase-wide and read/write-narrow method of recording. For the 200 TPI head, the erase pole-tip width is 5.2 milli-inches and the read/write pole-tip width is 2.8 milli-inches, while those for the 500 TPI head are 1.7 milli-inches and 1.0 milli-inch, respectively. Inter-track shields are used on both heads to minimize crosstalk.

Fig. 10 shows the track performance characteristic of the 200 TPI head with a head repositioning error of 1.0 milli-inch; Figs. 11 and 12 present the amplitude and peak shift characteristics of its readback signal at various bit densities. Data obtained by the 500 TPI head indicates that no appreciable head displacement can be tolerated. The written data at 2.0 milli-inch track centers, however, is good enough for information recovery. The readback signals of three adjacent tracks written and read back by this head at 500 TPI and 2,000 BPI are shown in Fig. 13. The readback signal amplitude and peak shift characteristics of this head are very similar to those shown in Figs. 11 and 12 for the 200 TPI head.

The intertrack shield has been found to be very effective in high track-density recording, for confining the widths of the erase track and of the write track, and for eliminating crosstalk. Its primary function is to provide a sufficiently low reluctance path, for shunting the excessive fringing field in recording, and for shielding the flux emanating from adjacent tracks in reading. The spacing between the shield and the pole tip depends largely on the track density and on the head-repositioning error.

Mechanical precision in fabrication is the present major limitation to the attainment of higher information storage density in magnetic recording. The head-gap length, pole-tip geometry and head-to-medium separation are the chief parameters affecting the achievement of better pulse resolution. Head-repositioning error and manufacturing tolerances are the major factors which limit the accomplishment of higher track density. With better head design and with proper choice of the recording method, the limitations imposed by mechanical tolerances can be reduced. In most cases, the use of a thinner recording medium with a more rectangular B-H characteristic gives a further improvement in pulse resolution.

## CONCLUSIONS

The effects due to head pole tip geometry in noncontact recording have been presented. Analysis and experimental data are in good agreement, indicating that significant improvement in pulse resolution is achieved by making the pole-tip length small and the angle between the pole-tip edge and recording surface large. Both features help to limit the spread of the writing field, and consequently reduce the trailing-field effect. This form of geometry also yields a sharper gradient of the head sensitivity function and therefore resolves a narrower readback pulse.

In addition, several recording methods and the effect of the head-repositioning error on the track density have been presented. Performance characteristics obtained from experimental data show no fundamental magnetic limitations in using very narrow tracks (up to 500 TPI) in noncontact recording.

Further, the value of the concepts and techniques developed has been demonstrated through their successful application in the design of high-density magnetic heads for noncontact recording. With good mechanical precision, eight hundred thousand to one million information bits of digital data per square inch in noncontact recording were obtained in this study.

## REFERENCES


1. Noncontact refers to head-to-medium separation of 100 microinches or larger.
2. D. F. Eldridge and A. Baaba, "The Effect of Track Width in Magnetic Recording." IRE Transactions on Audio, pp. 10-15, January-February, 1961.
3. Bit packing density is defined here as the number of pulses per inch where amplitude reduction starts, and track packing density is defined as the number of tracks per inch where crosstalk from adjacent tracks begins.
4. S. J. Begun, "Magnetic Field Distribution of a Ring Recording Head", Audio Engineering, Vol. 32, pages 11-13, December, 1948.
5. J. J. Miyata and R. R. Hartel, "The Recording and Reproduction of Signals on Magnetic Medium Using Saturation-type Recording," IRE Transactions on Electronic Computers, pages 159-169, June, 1959.
6. A. S. Hoagland, "Magnetic Data Recording Theory: Head Design," Communications and Electronics, Vol. 27, pp. 506-512, November, 1956.
7. Donald F. Eldridge, "Magnetic Recording and Reproduction of Pulses," IRE Transactions on Audio, pages 42-57, March-April, 1960.

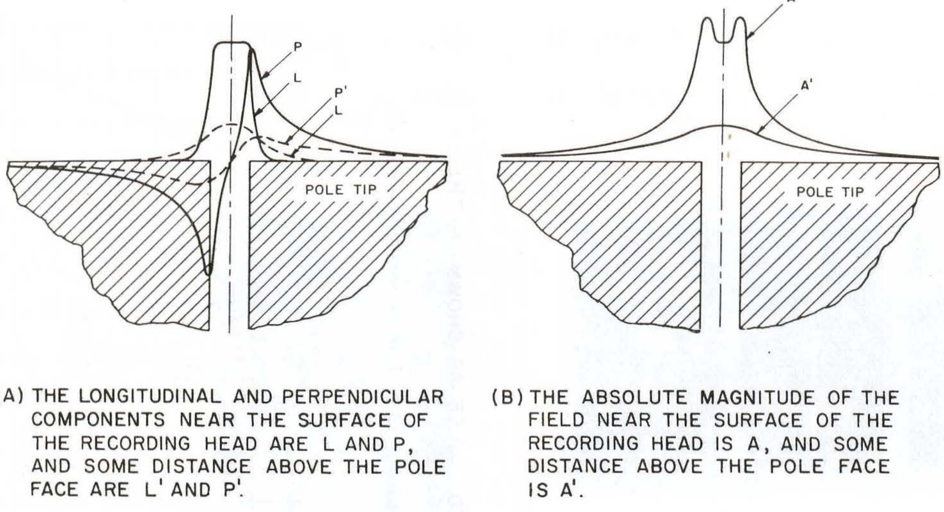



Fig. 1. Longitudinal and perpendicular components, and absolute magnitude of the field distribution.

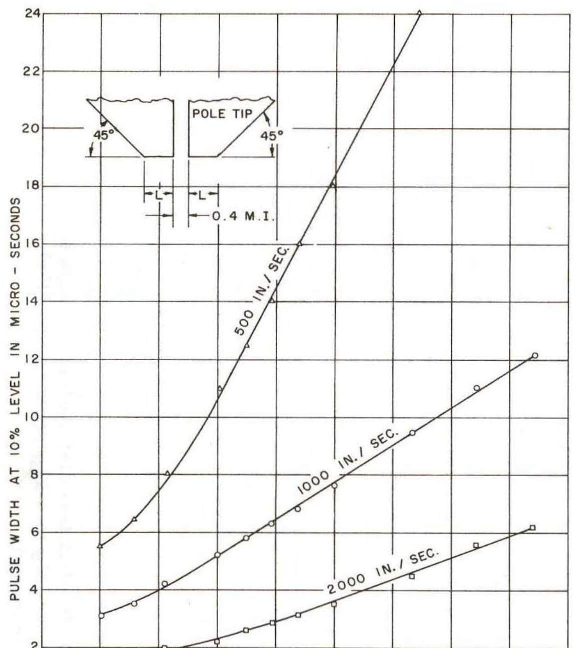



Fig. 2. Effect of head pole-tip length on readback pulse width.

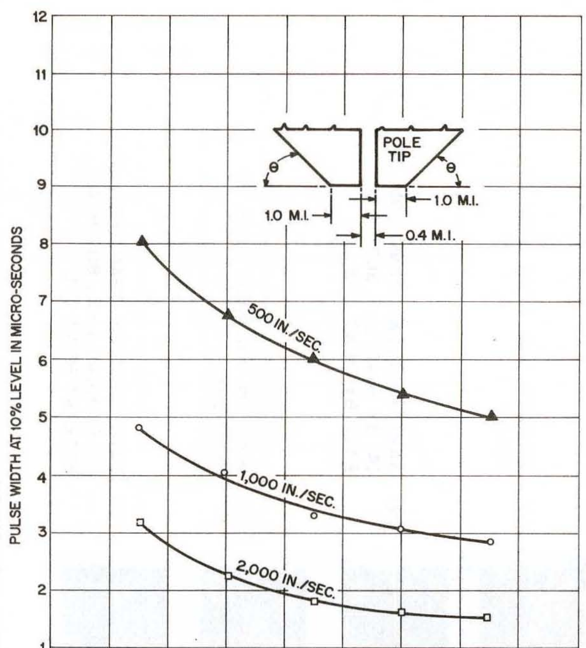
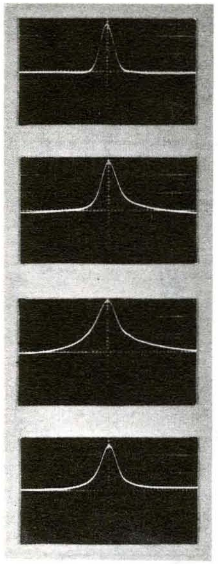



Fig. 3. Effect of the angle between head pole tip-edge and recording surface on readback pulse width.



(A) WRITTEN AND READ BACK BY HEAD L-1

(B) SAME WRITTEN TRANSITION OF (A) BY HEAD L-1, BUT READ BACK BY HEAD L-8

(C) WRITTEN AND READ BACK BY HEAD L-8

(D) SAME WRITTEN TRANSITION OF (C) BY HEAD L-8, BUT READ BACK BY HEAD L-1

POLE TIP LENGTH:
L-1 = 1.0 MILLI-INCH;
L-8 = 8.4 MILLI-INCHES.

Fig. 4. Readback pulses by two heads with different pole tip lengths.

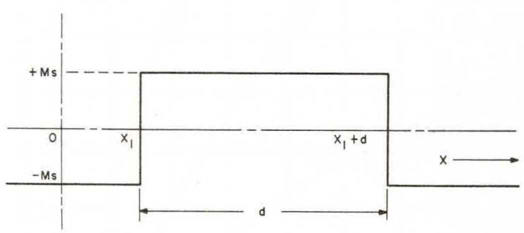
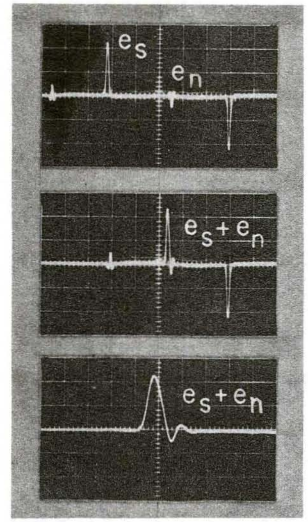
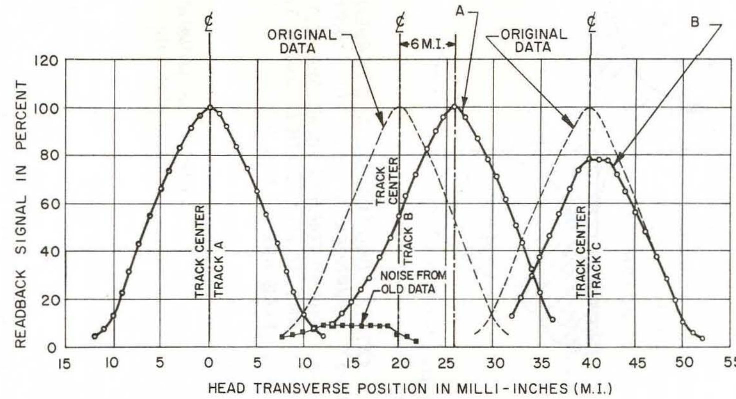



Fig. 5. Two step-function distribution of magnetization from - $M_S$ to + $M_S$, showing two "1's" (NRZI Recording).




AS THE DATA PULSE GETS TO THE POSITION OF THE SMALL NOISE PULSE, THE TWO ARE SUPERPOSED, RESULTING A DISTORTED PULSE AS SHOWN IN THE LOWER TRACE.

Fig. 6. Readback signal waveforms superposed.

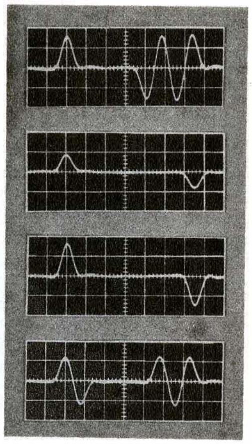



A- REWRITTEN DATA AT 6 M.I. OFF TRACK
B- SIGNAL LEFT AFTER ADJACENT TRACK WAS REWRITTEN AT 6 M.I. OFF TRACK

Fig. 7. Readback signal amplitude versus head transverse position by the erase-wide and read/write-narrow recording method.

NRZI WORD PATTERN

| | | |
|---|---|---|
| TRACK A | 1000011110 | AT 0 |
| TRACK B | 1111111111 | AT 0.020 IN. |
| TRACK B (REWRITTEN) | 1000000010 | AT 0.026 IN. |
| TRACK C | 1100001110 | AT 0.040 IN. |



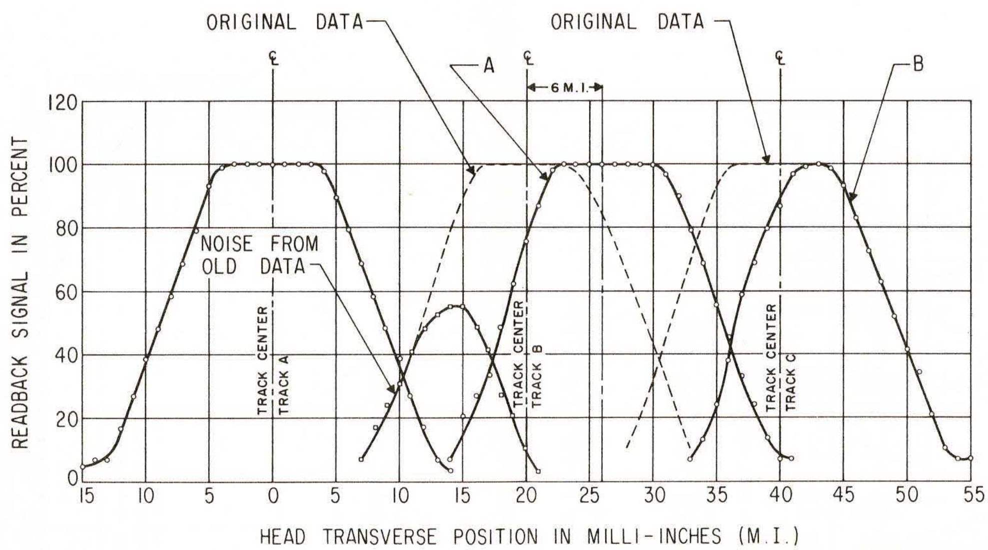
TRACK A AT 0

TRACK B AT 0.020 IN.

TRACK B AT 0.026 IN.

TRACK C AT 0.040 IN

Fig. 8. Readback signals of three adjacent tracks after center tract was rewritten at 6 milli-inches off track.




A. REWRITTEN DATA AT 6 M.I. OFF TRACK

B. SIGNAL LEFT AFTER ADJACENT TRACK WAS REWRITTEN AT 6 M.I. OFF TRACK

Fig. 9. Readback signal amplitude versus head transverse position, by the write-wide and read-narrow recording method.

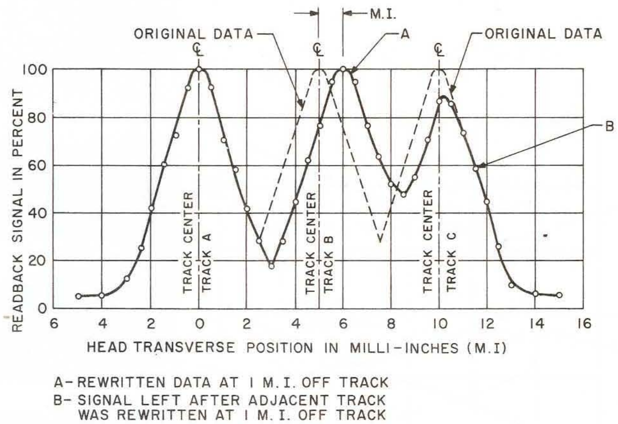



Fig. 10. Readback signal amplitude versus head transverse position (200 TPI).

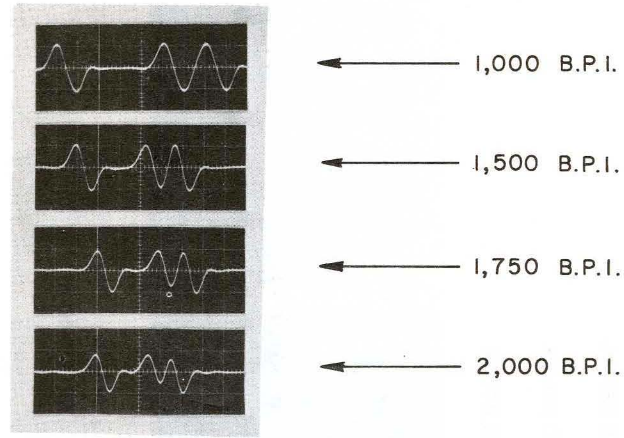



Fig. 12. Readback signal at different densities (200 TPI).



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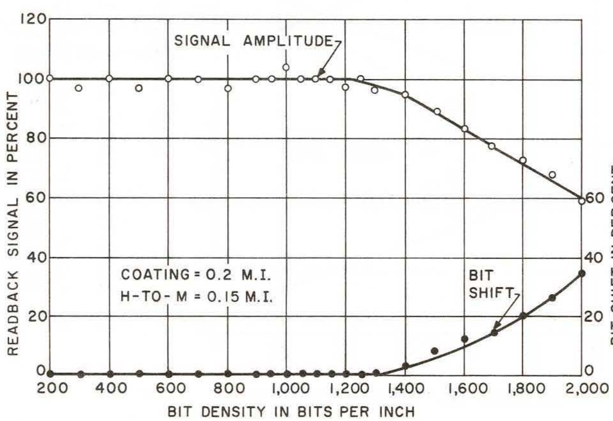


Fig. 11. Readback signal amplitude and bit shift versus bit density (200 TPI).

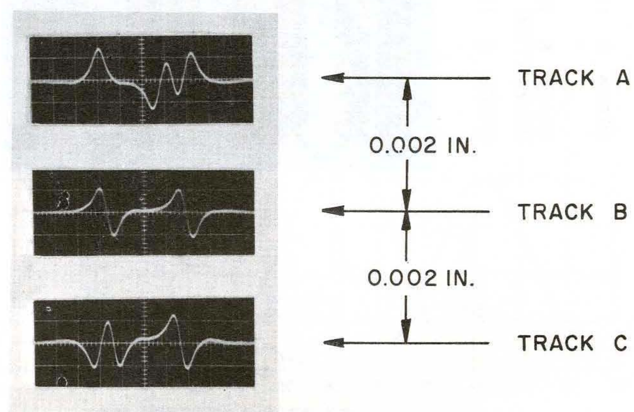


Fig. 13. Readback signals from three adjacent tracks (500 TPI and 2,000 BPI).