

A High Track-Density Servo-Access System for Magnetic Recording Disk Storage

Abstract: This paper is concerned with an investigation of the feasible track-density potential of random-access magnetic-disk storage where magnetic-head positioning is essential. Primary emphasis is given to a novel, servo-access concept (closed-looped head-positioning control which includes the record member) for track location and registration. This servo concept has been investigated as a means of making possible automatic tracking as well as precision positioning. Inherent in such an access control technique is an enhanced suitability for interchangeable record members. Included in the discussion are design and performance results of an access model operated at 154 tracks per inch.

Introduction

In random-access mass storage, a premium is placed on information availability. Thus, surface-area accessibility and information storage density are emphasized. Storage density is the product of the bit density per track times the track density on the recording surface. Increases in track density have as much value as equivalent gains in bit density in improving the ratio of capacity to access time.

Special techniques to maximize track density form the principal subject matter of this paper. In considering track-density limits when using magnetic head positioning devices, not only must the problems associated with narrow track recording be faced, but head positioning and head-to-track registration must be examined.

A servo-access concept, in which the feedback loop includes the storage surface, was chosen for study because of the inherent advantages this type of access control offers. By providing self-adjusting head positioning, the normal track-density limitation arising from the buildup of numerous cascaded dimensional tolerances is minimized. Further, with the surface included in the control loop, there is automatic compensation for mounting alignment tolerances with interchangeable or replaceable storage members. This latter memory feature may then be considered without having to accept a reduction in the setting of the track-density specification.

The starting point for establishing maximum track density is the minimum readback track width, set by the required signal-to-noise ratio. (A nominal 4-mil readback track width represented the lower limit for this

parameter in the experimental work reported here.) The track density then will be some fraction of the limit set by this recording requirement, after accounting for the accuracy of head-track registration. This investigation is directed to the head positioning and registration problem, since this represents a major and unique limitation to the full exploitation of magnetic recording for random-access storage.

The overall system involves both a coarse and a fine positioning control loop with automatic switching between them. The coarse loop utilizes a linear position measuring transducer, while the fine control loop involves feedback from permanent information located on the disk storage member. The fine-positioning scheme is essentially a null-seeking control system; i.e., the system input signal is equal to zero. The fine-positioning control system establishes the "following" characteristic of the access. This closed loop system is always in operation when transferring data into or out of a storage track.

A track centers spacing of 6.5 mils was selected for this feasibility study, giving 154 tpi (tracks per inch). This goal exceeds by a factor of three to eight the present track density specifications based on conventional "open loop" mechanisms. For the experimental setup a hydraulic servo valve was chosen to control the motion of a hydraulic piston rigidly coupled to the head assembly. It is possible with this access to move a head assembly, with an accuracy of about ± 0.5 mils, to any given track and achieve, as a characteristic access time, a speed of 59 milliseconds for a travel of 1.3 inches.

The servo-access system

The servo-access system is designed to select and register the head assembly automatically on any given one of a set of tracks by means of permanent control information on the surface. A combination of "coarse" and "fine" positioning modes is used. The coarse positioning control functions first and moves the access to the desired region, established by a linear positional transducer. The fine servo control then locates and automatically keeps the head assembly in registration on the selected track (from among those tracks included within the range of positioning tolerance of the coarse control), using information derived from the surface.

Figure 1 is a picture of the experimental servo-access model, showing the principal components except for the servo control electronics. The hydraulic piston, controlled by the hydraulic servo valve, supplies the motive force for positioning of the ganged head array. This head array includes a servo head, and, rigidly attached to it, fixtures for the mounting of data heads as shown. The linear differential transformer provides the positional error signal when in the "coarse" mode. The core of this differential transformer is rigidly linked to the hydraulic piston, hence to the head array. When in the fine-positioning mode, the hydraulic servo valve is operated by the error signal derived from the servo head reading the permanent control-pattern information located on the

Figure 1 Servo-access mechanism.



inner section of the disk. The width of this band sets the maximum access travel.

A basic requirement for such servo control is that the control-pattern be permanent. Since the magnetically recorded data are modified in file processing, the data per se could not provide a servo means; were it to be used in this fashion, a drift in track locations would inevitably occur which would gradually cause the access to become useless. A benefit from the use of a control-pattern band and a ganged head assembly is the localization of the servo control information on the surface. From the point of view of obtaining the necessary permanent control-pattern, the ability to use an inset pattern disk proved simple and convenient.

The design of the coarse-positioning loop is conventional; therefore, a general description of the overall servo-access system concepts will be confined to fine positioning.

• The control-pattern and the fine-positioning technique

The control-pattern can be characterized by a sample group number, n . The sample group number gives the "fine" selection power; i.e., a control-pattern of order n permits the automatic choice of one out of n tracks. A functional representation of the error signal polarity from a partial pattern for $n=1$ and $n=3$ is indicated in Fig. 2. The quantity $n=2$ applies to the experimental model and this case will be completely presented later. The pattern is constructed from a basic radial sector with alternating magnetization zones. The checkerboard structure results because a magnetic head is used for the servo pickup; thus only changes in magnetic state are sensed. The basic radial pattern is offset by increments of the track centers spacing, H , to provide a unique control sector for each sample time. (H is equal to the reciprocal of track density.) This fundamental control-pattern sector group is then regularly repeated to provide continuous control. Selection of a given sample time means that the control pattern is sampled by the control system only during the corresponding time slots. The servo head spans a radial band of less than nH and its output amplitude is proportional to the net width of the uncanceled error signal zone scanned.

A larger n permits an increasing inaccuracy in coarse positioning as well as reducing the number of discrete coarse positions needed. However, an increase in n will result in additional electronics as well as the acceptance of a reduction in the possible sampling rate by a factor of $1/n$.

The selection of the desired track involves an "odd-even" decision and the circumferential choice of sample time. This information is derived from the code of the specified track address. The odd-even selection determines whether a positive error control signal is to cause the access to be moved "in" or "out."

Assume that the coarse access motion has placed the servo head directly on the reference line indicated in Fig. 2 ($n=3$). This coarse address location provides access to one of three tracks. For the coarse address lo-

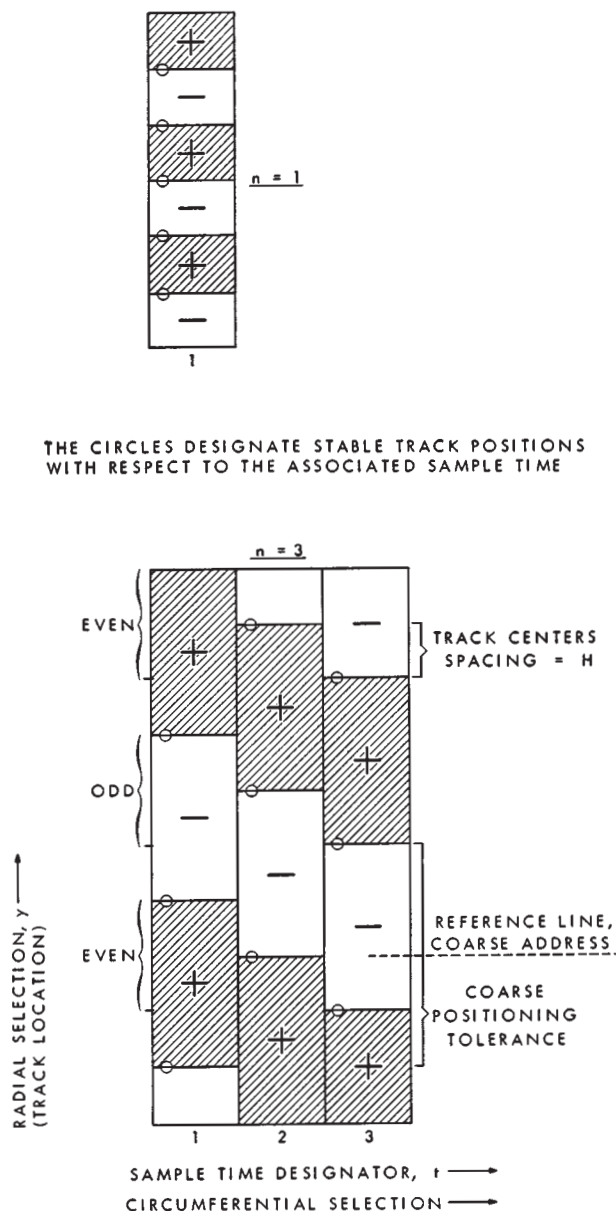


Figure 2 Functional representation of control pattern.

cation shown corresponding to an "even" set of tracks, a positive error signal (cross-hatched zone) must drive the servo head "out." In this example the servo system is directly in a null position if sample time "2" is selected. Should the track address select Sample Group 1, the servo head will, at the initial instant, be spanning a greater portion of the cross-hatched control region (during these time intervals). Hence, the servo head will begin to move out, stabilizing at the radial position (circled) associated with Sample Group 1. In this manner, any one out of three tracks can be chosen.

To properly access to these three tracks, the coarse-positioning system need only locate the servo head cen-

terline within the bracketed range indicated. For $n=3$ this situation permits a tolerance in coarse-positioning of ± 2 tracks. The general relation for an n -order control-pattern is:

$$n \geq 2T(\text{tpi}) - 1, \quad (1)$$

where T is the coarse positioning registration tolerance.

There is a fine-positioning registration error, P , that must be accounted for to preserve the required signal-to-noise ratio for magnetic recording. A dual-element data head provides a technique to cope with this positioning tolerance and is discussed here in order to explore the factors involved and their interrelation in the final setting of track density.

• Dual element data head

The dual element head structure is a write-wide read-narrow magnetic head pair.* Three specific reasons may be given for an interest in this type of unit.

1. It alleviates requirements on head-to-track registration.
2. It allows optimization of the magnetic elements with respect to one particular function, writing or reading.
3. It allows the possibility of obtaining an automatic read-back check when writing data through a simultaneous read-while-writing operation.

This paper is concerned only with feature No. 1.

For the purposes of analysis, the following definitions will be made:

W =effective write element track width,

R =effective read element track width,

P =maximum head-to-track registration error, and

c =centerline offset (misalignment) between the separate read and write elements.

Therefore,

$R+2P$ =effective width of band within which the reading track must occur, and

$W-2P$ =effective width of guaranteed re-recorded band.

This band will always contain only the most recently recorded information.

These bands are symmetrically located about their own reference centerlines for this recording track; however, the read and write element centerlines may be offset by c . Now with such a dual element structure the deleterious effect of P upon the S/N (signal-to-noise) ratio can be circumvented by requiring that the following inequality exist:

$$R+2P \leq W-2P; c=0. \quad (2)$$

With this condition the read element is always con-

strained to fall within the "re-recorded band." This relation gives

$$W=R+4P. \quad (3)$$

The restrictive condition that establishes the relation between W and R (in order to insure that the read element will remain within the re-recorded band) when c is not equal to zero arises on that side of the recording track towards which the read element centerline is biased. Here,

$$W/2 - P \geq R/2 + P + c$$

or

$$W \geq R + 4P + 2c. \quad (4)$$

Since the signal-to-noise relations arising from misregistration are not further compounded by the presence of adjacent tracks bordering the one under consideration, then

$$(\text{tpi})_{\max} = (W_{\min})^{-1} = (R_{\min} + 4P + 2c)^{-1}. \quad (5)$$

The dual element head structure is seen to represent a valuable concept to exploit, even with a high-precision servo system. A minimum R is set by the required S/N ratio on readback. The null characteristics of the servo access establish P and thereby the maximum usable track density. The required sample group number n is then determined by Eq. (1).

• Servo head

One design parameter of the servo head is the head width, r . The quantity $r_{\min}$ must be much greater than the effective "line widths" in the permanent control-pattern placed on the surface in order to achieve a stable control system. As r is increased, a more effective integrating action of any existing line distortion results. Quantity $r_{\max}$, from a practical standpoint, is equal to nH . That is, the error-control signal is at a maximum whenever the servo head is more than $\pm r/2$ off track and less than $\pm(nH/2 - r/2)$. Within $\pm r/2$ off center, the servo head error signal is proportional to its "off track" displacement. A zero error or null condition is actually an error voltage range within which the control system is insensitive. The associated "radial" positional variation ($+P$) represents the tolerance in the servo head position.

• Error switching between control loops

In Fig. 3 a functional presentation of the control-pattern is shown (for $n=2$) where the plus and minus signs indicate the relative polarity of the error signal. Position i denotes a defined coarse-access reference position. This position is seen to be centrally located with respect to the two corresponding addressable tracks. Quantity j denotes the tolerance range of the coarse positioning loop while k and l denote the nearest stable positions, other than i , for the fine servo control operating on sample time 1. Quantity m denotes the limits beyond which a coarse null detector will reset and again place the coarse

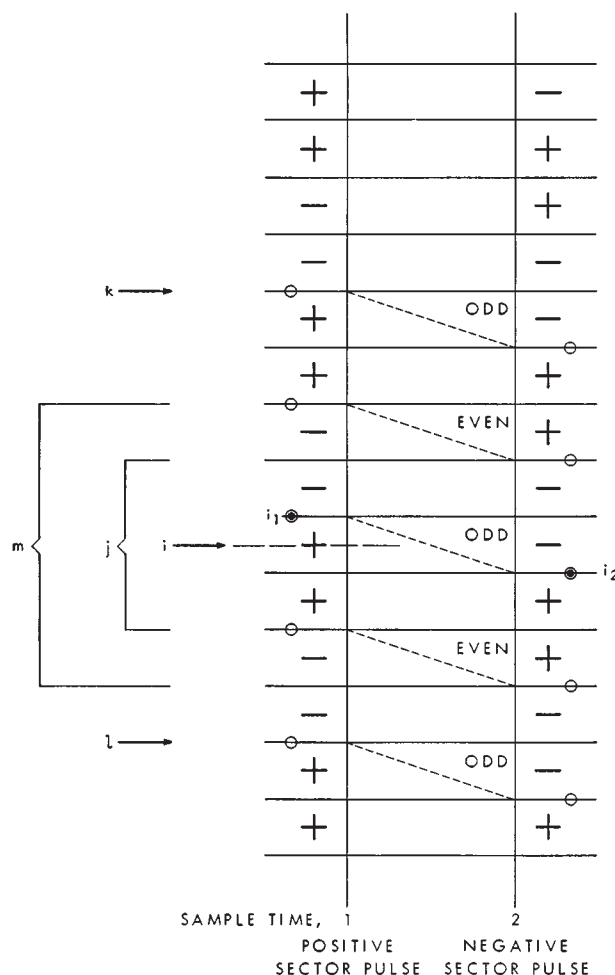
*A wide erase, read-write narrow structure is equivalent for purposes here.

loop in control. These latter limits are $\pm 2\frac{1}{2}$ tracks from i or ± 1 track beyond the zone within which the coarse servo system positions.

The sequence of events in track positioning with i_1 , the selected track address, is as follows:

1. The error switch connects the coarse-positioning circuits into the access feedback loop.
2. The servo head (hence access) is driven to some position within the limits denoted by j .
3. When the coarse error signal is reduced in amplitude to a magnitude corresponding to less than a track width offset from a stable coarse null, the coarse null detector operates the error switch to disconnect the coarse control loop and connect the fine positioning servo circuits in the access control loop.
4. The fine-positioning control loop normally positions the servo head exactly to i_1 .

Figure 3 Coarse-fine error switching requirements.



$n = 2$ CONTROL PATTERN
0 = STABLE TRACK LOCATIONS

5. If the fine-positioning control cannot prevent an overshoot excursion beyond the limits denoted by m , as a result of the access mechanism motion at the time of error switching, the coarse null detector will reset. Coarse-positioning control will then take over again to reposition the access. Without this provision the fine-positioning control loop would otherwise cause the access to drive towards k or l . This hysteresis-like phenomenon in coarse-fine switching also permits the writing and reading of data with the access following track "weaving" up to $\pm (5/2)H$ about the coarse address reference line.

An advantage of having two control modes, coarse and fine, is that it permits the benefits of a servo access for final positioning with no more complexity than actually justified.

Experimental model

• Coarse-positioning

A block diagram of the coarse-positioning servo loop is shown in Fig. 4. It is composed of four basic functional blocks: the addressing block; the linear position transducer; the error-signal conversion block; and the access mechanism.

The address is entered by setting up the resistor adder shown in Fig. 4 so that the resistance is proportional to the binary-coded address. A voltage proportional to the current through the primary of the linear differential transformer is amplified by the first operational amplifier. The output (a constant voltage) is applied to the input of the resistor adder and also to one end of the divider network R_1R_2 . The voltage appearing at the output of the second operational amplifier is 180 degrees out of phase with that of the first amplifier and has an amplitude dependent on the address. This output is connected to the other end of the divider network, causing the center point to assume a magnitude dependent on the selected address. This voltage is then the address reference voltage, e_1 . It is a 1-kc voltage which will be zero when the center track is addressed and of maximum amplitude, but opposite in phase, at the two extreme track addresses. Linearity is essentially that of the resistor adder, or 0.1%.

The gain control in the second operational amplifier is used to scale the address reference voltage so that proper track spacing is obtained. By summing e_1 and the position transducer voltage, an error signal, e_2 , is obtained. The magnitude of e_2 is proportional to the difference between the desired address and the present servo head location and the phase of e_2 indicates the direction of the access displacement from the selected position. This error signal is demodulated and converted to a differential drive current for the hydraulic servo valve.

• Coarse-fine switching

A block diagram of the overall servo-access system is shown in Fig. 5. The stimulus for mode switching is the coarse-positioning error signal. This signal is monitored

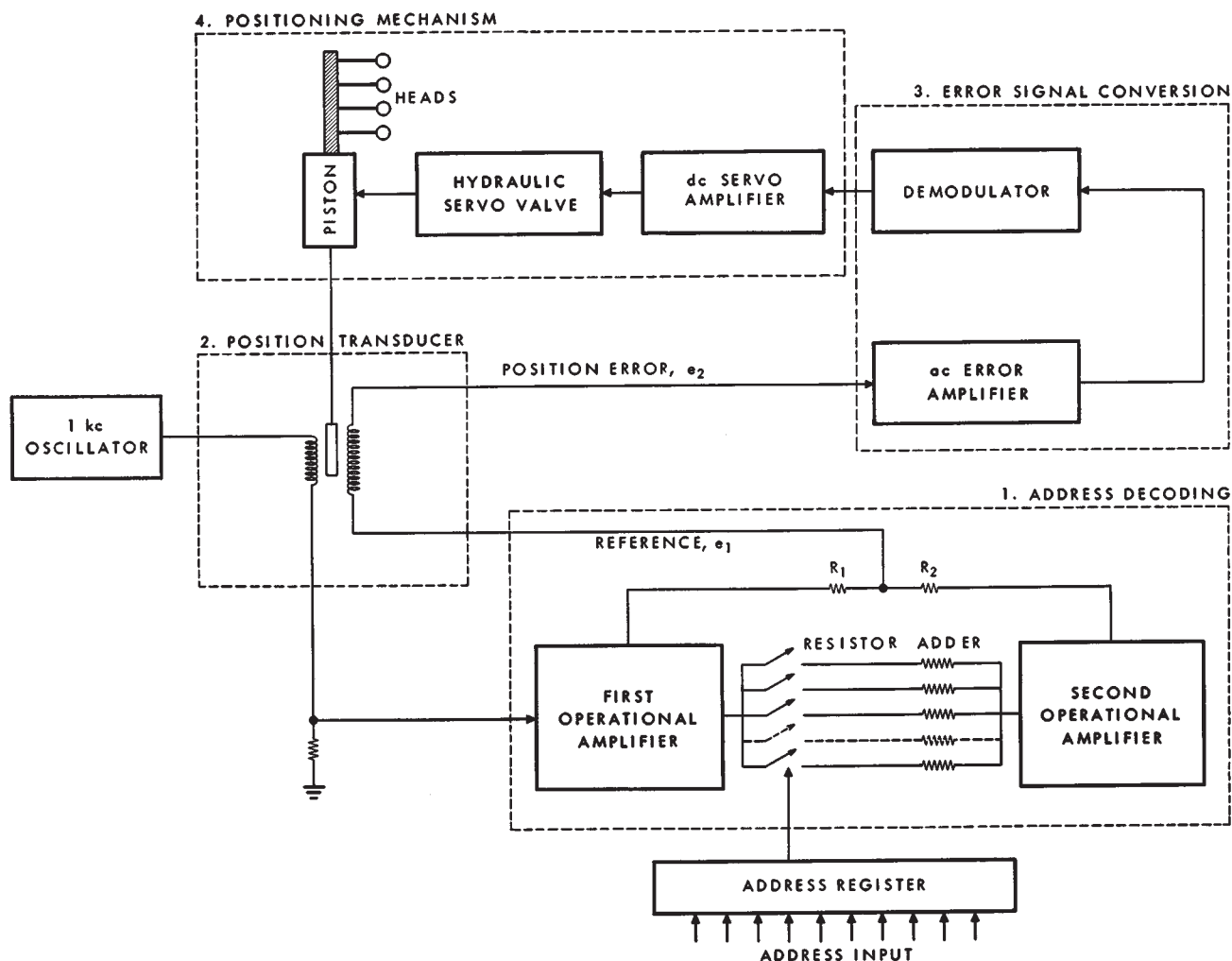


Figure 4 Block diagram of coarse-positioning servo loop.

at all times by a null detector. In the experimental model, when operating under coarse-positioning control, the coarse error signal causes the detector to switch to the fine-positioning mode when the head array is approximately 0.005 in. from the desired track location. Gain is simultaneously reduced on the coarse error amplifier so that control will not be switched back to the coarse-positioning mode until the heads are 0.016 in. from the specified track location. The wider excursion of the head array before re-switching to coarse-positioning control allows the data heads to follow track runout up to 0.016 in. (from the null location defined by the coarse-positioning transducer). This hysteresis effect also permits the switching to fine-positioning control to occur with a minimum of initial access error in position and velocity.

• Fine-positioning

The control pattern is composed of 100 wedge-shaped sectors spaced around the inner radius of the disk. Each sector is a matrix of small squares, alternate ones

recessed below the normal disk surface. The recessed areas are some 0.0005 in. below the surface, the pattern being formed by a photo-etching process. Figure 6 shows the etched pattern as it appears on the inner portion of the experimental disk.

The readback error signal derived from the pattern is shown in Fig. 7. Sensing is accomplished by a magnetic head through which a dc bias current is passed. As the wall of an etched area is traversed, the magnetic coupling between the servo head and surface changes and a voltage is induced in the head. Superposition applies, so the polarity and amplitude of the error signal are determined by the fraction of the head width scanning etched to nonetched regions as compared to that fraction simultaneously traversing nonetched to etched regions. Typical waveforms are shown for the servo head located on either side of and precisely on a track centerline. Three things may be noted about the waveforms:

1. The first (timing) pulse is always present, indicating the beginning of a control-pattern group.

2. Pulses 3, 5, 7, 9, and 11 are five pulses of the same polarity which are sampled to yield the corrective servo error signal. (The even-numbered pulses are not used.) This "multiple" burst sampling reduces fine-positioning sensitivity to possible control-pattern defects by providing an averaging effect.
3. The sector mark track with its associated fixed head yields a series of pulses, alternately positive and negative, which precede the timing pulses and provide for sample group selection as well as a "ready" signal.

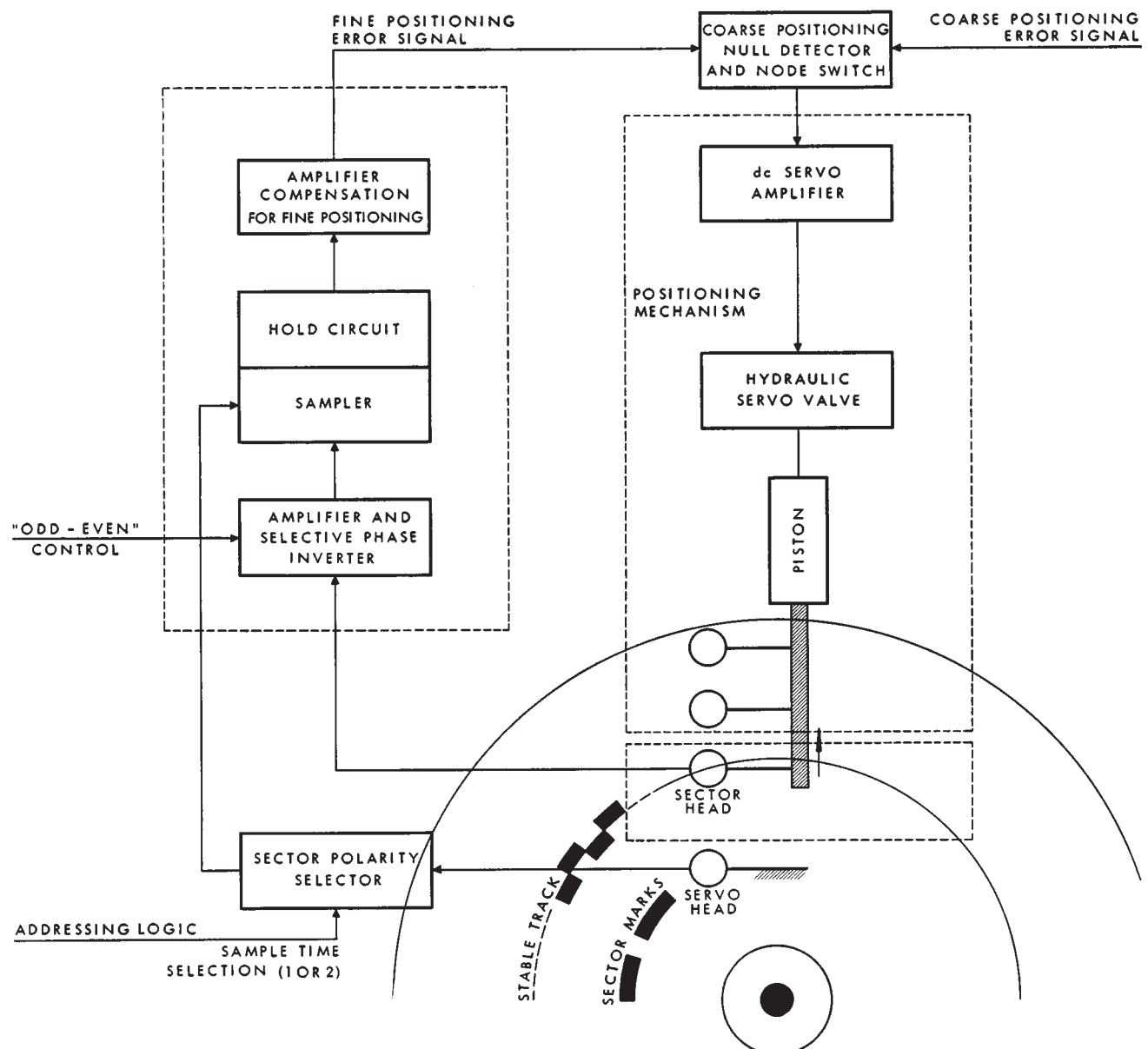
As seen in Fig. 6 the control-pattern consists of two interleaved sets of matrices, radially offset by 0.0065 in. Thus, sampling of one set selects a set of track locations

with a 0.013-in. centers spacing. Sampling of the alternate matrices gives an interlaced set of tracks, also on 0.013-in. centers.

The incoming servo head error signal is first applied to a selective phase inverter, controlled by the address decoding logic (Fig. 8). For a given error-polarity direction-of-travel relation (e.g., heads driven *toward* the center of the disk for a positive error signal at sample time), stable track locations are located 0.026 in. apart on a given set of sampled matrices. In order to servo on the interlaced tracks associated with this sample time, polarity inversion is required.

Conversion of the error pulse train to a dc signal, for control of the servo valve, is illustrated in Fig. 8. Gating signals are generated to sample the peaks of the differ-

Figure 5 Block diagram of fine-positioning loop.





ential servo error signal. As previously explained, this sampling begins with the third pulse in the train. The normal or the inverted servo signal is converted to a dc error voltage in the hold circuit. The time constant of the hold circuit is adjusted to obtain an average of peak values of the five samples. This procedure reduces the effect of one bad readback pulse on the net error signal.

Generation of the sampling pulses is also shown in Fig. 8. The pulse train is initiated by setting the first bistable multivibrator with a logically controlled synchronizing pulse (from the sector mark track) and resetting it with the first pulse from the next servo control-pattern matrix. The sample pulse train is obtained from the output of a monostable multivibrator triggered by a gated oscillator. The first monostable multivibrator provides a delay to properly time the sample pulses with respect to the servo-head error signal (the second monostable multivibrator gates the oscillator).

• Performance

There are two performance criteria to consider:

1. The response time of the servo-access system in moving from one track to another.
2. The ability of the servo-access system to come to a null and then keep the head array aligned on track.

On the experimental model, the time for a 1.3-in. travel (maximum movement) is approximately 35 milliseconds. This is the time from change of address until

operation of the null detector occurs the first time. A terminal velocity during coarse-positioning was reached approximately 5 milliseconds after start of motion. The deceleration phase under fine-positioning control frequently was not rapid enough to avoid "overshooting" the desired track and causing the system to switch back into the coarse-positioning mode. This "overshoot" behavior may occur as many as three times in an access cycle and consume 10 to 20 milliseconds, depending on the access velocity and the actual error signal in the sample and hold circuit when the switching transition is made between control modes.

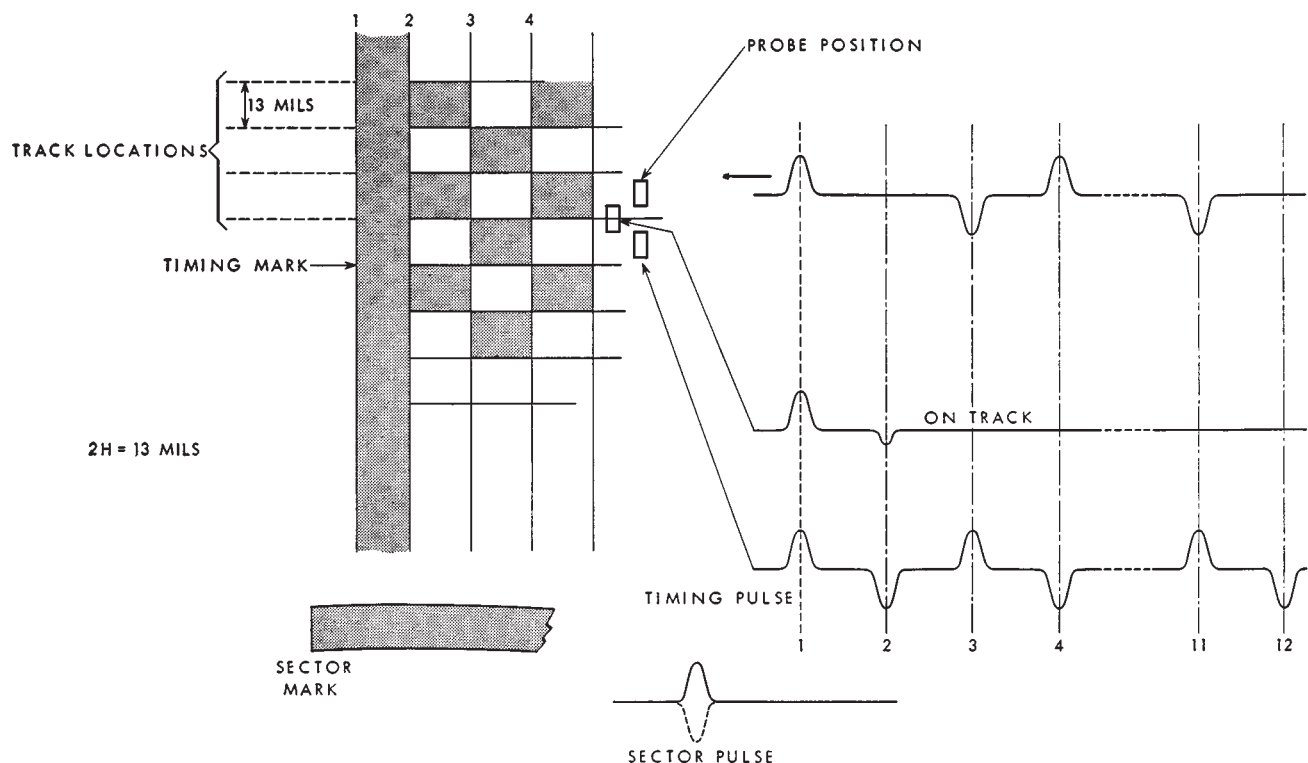
Once fine-positioning control exists, the key question is that of track-following ability. The tracking performance of such a disk-referenced servo system must be measured relative to the disk itself. This fact presents difficulties in making accurate measurements, because the displacements under consideration are of the order of tenths of mils. With the servo access following 0.0006 in. of total indicated runout at 20 cps (the disk rotational frequency), the maximum track registration error was within 0.0008 in.

Components of prime importance in setting response and positioning performance of this proportional servo system were the hydraulic servo valve and actuator (hydraulic piston) assembly. Fine-positioning accuracy was limited by actuator hysteresis (valve and piston).

Summary

This paper has attempted to present general considera-

Figure 7 Readback signal derived from etched pattern.



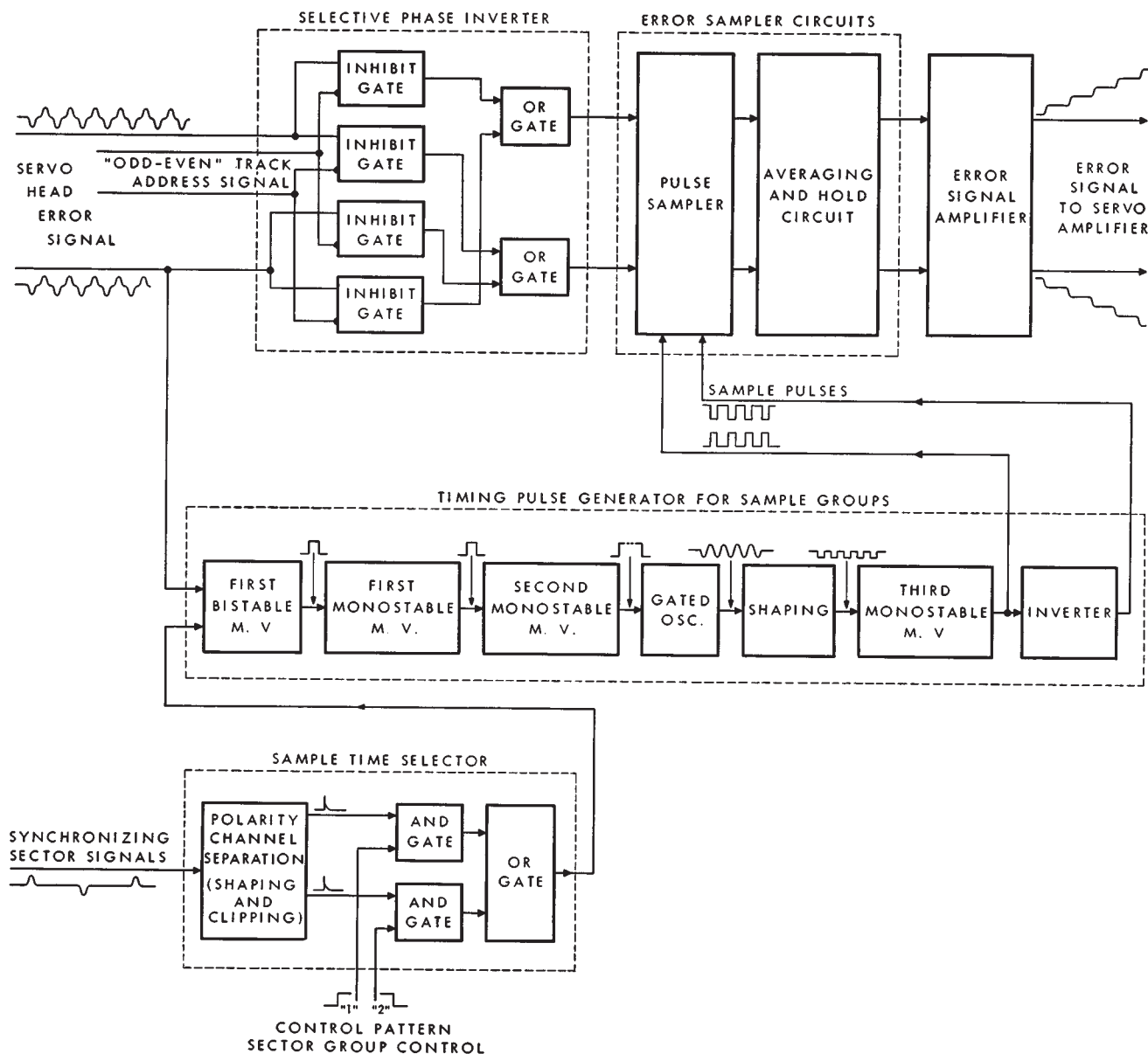


Figure 8 Detailed block diagram of fine-positioning loop.

tions and approaches applicable to maximizing track density. In particular, it was felt desirable to present within the same paper a discussion of the dual element recording structure and a new servo-access concept being explored, since they offer significant promise for radically advancing storage density realizable in random access magnetic recording memories. An experimental access model has been built and tested to define key problems in terms of practical exploitation.

It has been possible to register a head assembly on track to better than ± 0.8 mils while following up to 6 mils of track runout with a cyclic frequency of 20 cps. With a 6.2-mil write—3.7-mil read dual-element head structure, 154 tpi has been demonstrated feasible in terms of head-access registration with an accessing

speed of fifty milliseconds per inch. Thus a new level of track density and hence mass storage performance can be anticipated through efforts on access design.

Acknowledgments

The overall activity presented in this paper represents the results of the work of many people. In particular, H. R. Kerby was instrumental in the servo electronics aspects, while J. O. Hildebrand was the principal contributor in the mechanical phases of the servo unit. In addition, G. C. Bacon and K. E. Haughton made significant contributions to this program and their efforts are also gratefully acknowledged.

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