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TECHNICAL REPORT

Code: 211.076.100
Date: February 24, 1956

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# THE ACCESS MECHANISM FOR THE 350 RANDOM ACCESS MEMORY

by

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February 24, 1956

## ABSTRACT

This report is about the access mechanism of the 350 Random Access Memory. The general arrangement and the details of the electrical control circuitry are covered.

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SAN JOSE, CALIFORNIA

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## Introduction

Probably the one portion of the 350, Random-Access Memory, about which more concern has been expressed and toward which most inquiries have been directed is the access mechanism which positions the magnetic heads to the information tracks. This report has been prepared to help clarify this situation.

Because feedback-control systems may be unfamiliar to some, the system is presented first in a general fashion and is then followed by a detailed account of several aspects of the system.

Since the access time is of such fundamental importance in any memory device, one of the aspects treated in detail is the fundamental speed limitations of the access mechanism and control system used. In addition, details of relay circuitry and of the control-system dynamics are discussed.

More detail is included than is generally desired in order to provide information for specific interests.

## Physical Arrangement

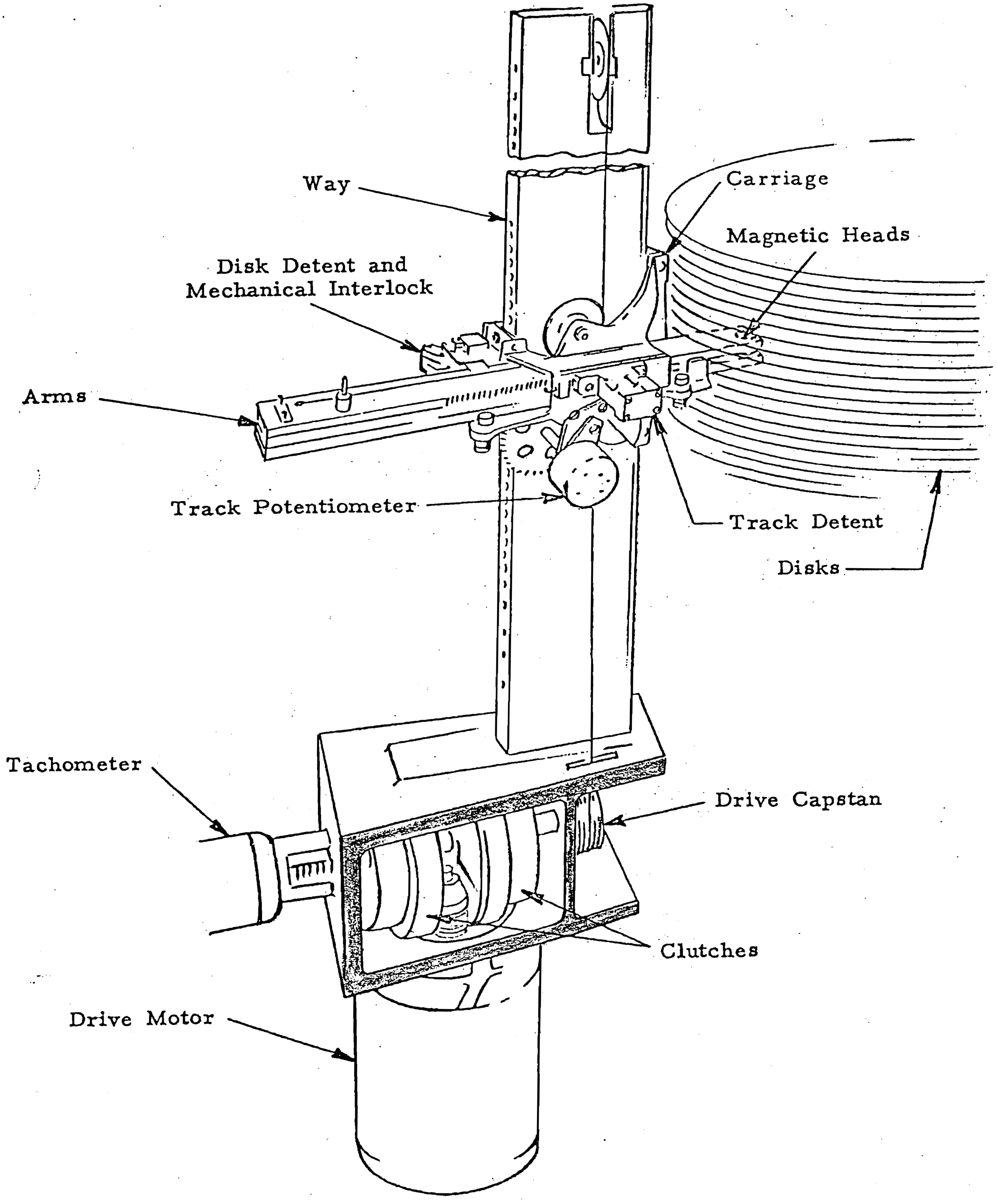
The basic function of the access mechanism of the 350 is to postion a pair of magnetic heads to any track on any disk of the random-access machine. The fifty recording disks are stacked on a vertical axis. The magnetic heads are mounted in a pair of arms which have radial freedom.

To position the heads to any track on the disk array, two drive motions are used. Positioning to the desired disk is accomplished with a vertical drive, and to the desired track with a radial drive. Figure 1 illustrates the mechanical portion of the access mechanism.

The arms are guided, for radial motion, in bearings on the carriage. Within these bearings the arms are capable of about six inches of radial motion. The inner five inches position the heads over the disk recording area. When the arms are in their outermost position, the arms are completely outside of the disks. This is the position the arms are in during vertical-drive motion.

The carriage, during vertical motion, slides on a vertical 'way'. At each of the fifty disk positions a detent hole is provided in the way. A pneumatic-detent piston is energized upon arrival at the desired disk. This detent, by means of a mechanical linkage, controls an interlock which frees the carriage and locks the arms for vertical drive, and frees the arms and locks the carriage for radial drive. The arms are capable of being freed only when the carriage is positioned properly at a disk and the carriage is capable of being freed only when the arms are completely outside of the disks. Thus, a safe interlock is provided to prevent mechanical damage to the disk assembly.

The driving force is provided by a pair of magnetic-powder, motor-driven, counter-rotating clutches. These clutches have a common-output shaft on which is located a drive capstan. A small, steel cable connects the drive capstan to the arms through a system of three pulleys. When the arms are locked the carriage is free and clutch torques result in vertical-drive motion.




MECHANICAL ACCESS SYSTEM.
FIGURE 1

Similarly, when the carriage is detented the arms are free and the same clutches control radial motion. In addition to the detent for locking the carriage, a detent is provided to position the arms to their final accuracy. This feature greatly relieves the positioning requirements of the position-feedback controller.

The clutches are controlled by a feedback-control system. Position signals for the radial and the vertical drives are obtained from potentiometers on the carriage and on the way, respectively. For stabilization of the feedback loop a velocity signal is obtained from a tachometer located on the clutch-output shaft. A d-c control system is used. The use of relatively large voltages on the potentiometers essentially eliminates any drift problems.

Hereafter, the radial drive will be referred to as the track drive as it is associated with selection of a track, and the vertical drive will be referred to as the disk drive.

<u>Electrical Control System</u>

The control system energizes the two clutches so as to properly position the arms. The basic system used for track drive and for disk drive is the same. However, because the distance between disks is greater than the distance between tracks, and because the masses of the arm and of the carriage are different, the dynamics of the two drives differ.

To explain the operation of the control system the disk drive will be used.

The disk-drive potentiometer is a linear-motion potentiometer. The resistance element is attached to the frame; the wiper is attached to the carriage. Fifty taps are equally spaced along the resistance element such that when the wiper is adjacent to a tap it is positioned to a corresponding disk. A reference-voltage supply, which is electrically floating, establishes a voltage gradient along this resistance element. One of the fifty taps is electrically grounded through the disk-address-relay points. When the wiper is above this tap it sees a positive voltage, when below, a negative voltage. This voltage is fed into the control amplifier which, in turn, energizes the appropriate clutch to drive the wiper toward zero voltage. Because of the kinetic anergy stored in the moving carriage, it is necessary to anticipate arrival at the correct disk so the stopping clutch can be energized early enough to prevent significant overshoot. This anticipation is provided by the tachometer voltage. The tachometer voltage is subtracted from the potentiometer voltage. Thus, when the carriage is moving toward the correct disk a voltage reversal is accomplished prior to the arrival. This energizes the stopping clutch. As the stopping clutch is energized, the carriage slows down decreasing the tachometer voltage, concurrently, the potentiometer voltage is decreasing toward zero. With proper adjustment, the carriage can be made to come to a stop nearly simultaneously with the potentiometer voltage reaching zero.

To position the arms to a new address a few logical choices must be made. If the new address is on the same disk it is only necessary to radially drive the arms to their outermost position, switch to disk drive, go to the correct disk, then drive radially again to the correct track.

The remainder of this report will cover in much greater detail the speed limitations, the relay-addressing system, the control-system logic and the feedback-control-system dynamics.

## Access Time Considerations

The limitations on the speed of access will be considered in this section. Since the various system parameters enter into the access time, numerical values will be substituted after some preliminary equations and ideas are developed.

The basic system consists of a drive shaft on which is mounted the output members of both magnetic clutches, the tachometer rotor, and the drive capstan. The drive capstan, in turn, is coupled to the carriage (for vertical motion) and to the arms (for radial motion) by means of a flexible-steel cable. The radius of the drive capstan determines the relative velocity of the drive shaft to the carriage (or the arms).

The inertia of the system referred to the drive shaft is:

$$J = J_d + R^2 M \qquad (1)$$

where,

$J_d$ = inertia of drive shaft
$R$ = radius of the capstan
$M$ = mass of driven member

The optimum capstan radius can be determined by finding the radius which causes the driven member to move the furthest for a given torque in a given time.

The driven shaft turns through an angle. $\Theta$

$$\Theta = \frac{T t^2}{2 ( Jd + R^2 M )} \qquad (2)$$

where,

T is torque applied to drive shaft

t is time

The driven member travels a distance, $x = R\Theta$ or:

$$X = \frac{R T t^2}{2 ( J_d + R^2 M )} \qquad (3)$$

Maximizing x with respect to R:

$$\frac{dx}{dR} = O = \frac{2 ( J_d + R^2 M ) T t^2 - 4 R^2 MT t^2}{4 ( J_d + R^2 M )^2}$$

$$J_d = R^2 M \qquad (4)$$

Thus, the radius should be chosen to make the two inertias equal. It can be shown that this same radius is also optimum for the case where the driven member accelerates to its terminal velocity, runs at constant speed and then decelerates to a stop.

The mass for disk drive is about three times the mass for track drive. Therefore, the capstan radius should be about seventy per cent larger for the track drive. A compromise radius must be chosen. Fortunately, the optimum is a broad one, but this analysis does point out that an improvement in access speed cannot be obtained by going to a larger capstan.

The clutch-input members are driven by a motor at nearly constant speed. If a clutch is engaged long enough to bring its output member up to this rotational speed, the drive cable moves at about 100 inches per second. Whether the cable gets to this terminal velocity or not depends upon the torque available and the distance the driven member is to move.

To simplify the calculations somewhat all parameters now will be referred to the driven member. The idealized conditions given here will permit evaluation of the maximum access speeds possible with this access system.

When the available force is insufficient to get the mass up to the terminal velocity, acceleration must take place for one-half the travel distance and deceleration for the other half. For this case the travel time is expressed as:

$$t = 2\sqrt{\frac{S\,M}{F}} \qquad (5)$$

Where, S = distance to be travelled.
M = mass referred to the driven member, including drive-shaft inertia.
F = available driving force.

When the available force is sufficient to get the mass up to the terminal velocity in less than one-half the travel distance, a portion of the travel can be accomplished at the terminal velocity. For this case the time to accelerate is:

$$\frac{V}{A} = \frac{VM}{F} \qquad (6)$$

where, V = terminal velocity
A = acceleration

The same time is required to decelerate. The average velocity during these times will be $\frac{V}{2}$ thus, the time for the distance travelled at full speed will be:

$$\frac{S}{V} - \frac{VM}{F}$$

The total time to travel the distance S on disk or track drive is:

$$t = \frac{S}{V} + \frac{VM}{F} \qquad (7)$$

To travel from one disk to another:

$$t = \frac{S}{V} + \frac{3VM}{F} \qquad (8)$$

When a terminal velocity of 100 inches per second is used with our present clutches, equation 8 holds for the maximum travel case, i.e. inner track on lowest disk to inner track on highest disk. (32 inches) Substituting numbers into equation 8 yields a drive time of:

$$t = 0.32 + \frac{2.73}{F} \qquad (9)$$

where, F is the drive force in pounds and must be greater than 15 for this expression to be valid.

M = 3.5 pounds is used.

This gives times from .374 seconds to .502 seconds for forces of 50 and 15 pounds, respectively.

To these idealized times must be added other time required in the system. Due to the inductance in the clutch coil about .020 seconds is required to develop the output torque. Although, the same delay can be anticipated in stopping, the control problem is more difficult and at least the same time need be added for stopping on each of the three drive motions. (On starting, a clutch is turned full on whereas on stopping, both clutches are called upon to cause the driven member to follow a certain position-velocity trajectory) This delay adds .120 seconds to the drive time. Upon completion of the disk drive a mechanical detent is engaged, this takes about 0.025 seconds. Upon arrival at the correct track a track detent is engaged and the heads are brought to the disk surface. The time required for this, plus a safety-factor delay, requires about 0.080 seconds.

Totaling these times gives an access time ranging from .600 to .720 seconds being possible, with the ranges of drive force given above, for traveling to the inner track on the bottom disk from the inner track on the top disk or vice versa. The power limitations come into the picture when the terminal velocity is increased significantly. In starting, the accelerating-clutch slip speed goes from 100 radians per second to zero; whereas, the stopping-clutch slip speed goes from 200 radians per second to 100 radians per second when the cable velocity is 100 inches per second. At 50 inch-pounds torque the energy required is:

$$50 \text{ in} - \text{lb} \times 50 \frac{\text{rad}}{\text{sec}} \times \frac{.91}{50} \text{ sec} = 45.5 \text{ in} - \text{lb starting}$$

$$50 \text{ in} - \text{lb} \times 150 \frac{\text{rad}}{\text{sec}} \times \frac{.91}{50} \text{ sec} = 136.5 \text{ in} - \text{lb stopping}$$

$$(45.5 + 136.5)\ 3 = 546 \text{ in} - \text{lb energy of access lost in clutches}$$

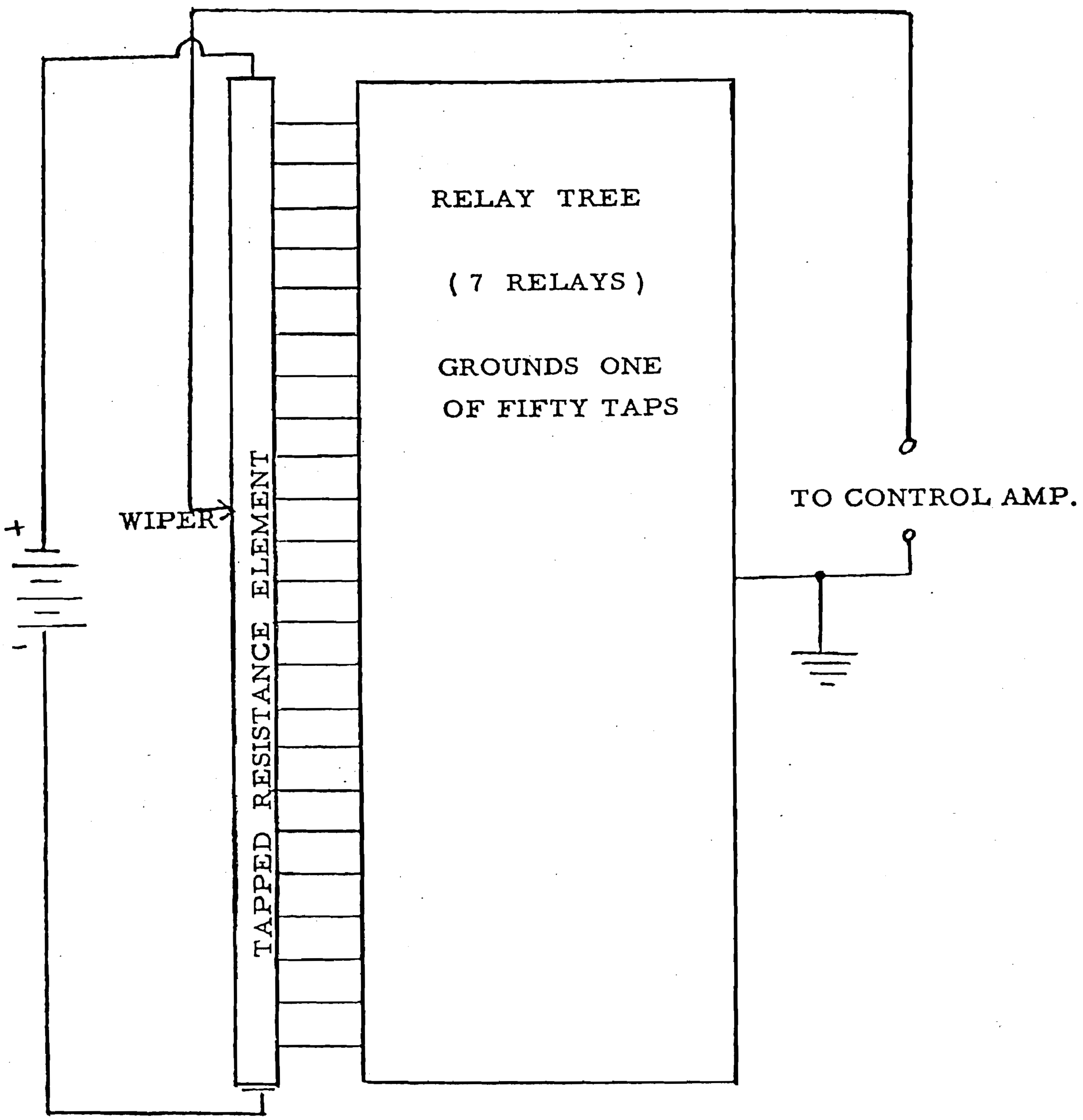
due to accelerating and decelerating. About 100 in-lb of energy must be added for frictional losses. For 0.600 second access time this gives an average-power dissipation of 0.163 horsepower during access. If the terminal velocity is doubled the energy of accelerating and decelerating quadruples. The potential access time drops to about 0.49 second, whereas, the average-power dissipated during access rises to 0.71 horsepower. The average-power dissipated during shorter accesses is even greater, since the power is lost during accelerating and decelerating periods. If the duty cycle of the access mechanism is low enough, these access times are possible since the average power drops. However, clutch life under these stringent conditions did not look promising and complications in driving the clutches with the drive motor made selection of our present drive speed more desirable.

The access times developed in this section are based upon proper adjustment. The significance of these adjustments will be developed in the section dealing with the dynamics of the control system.

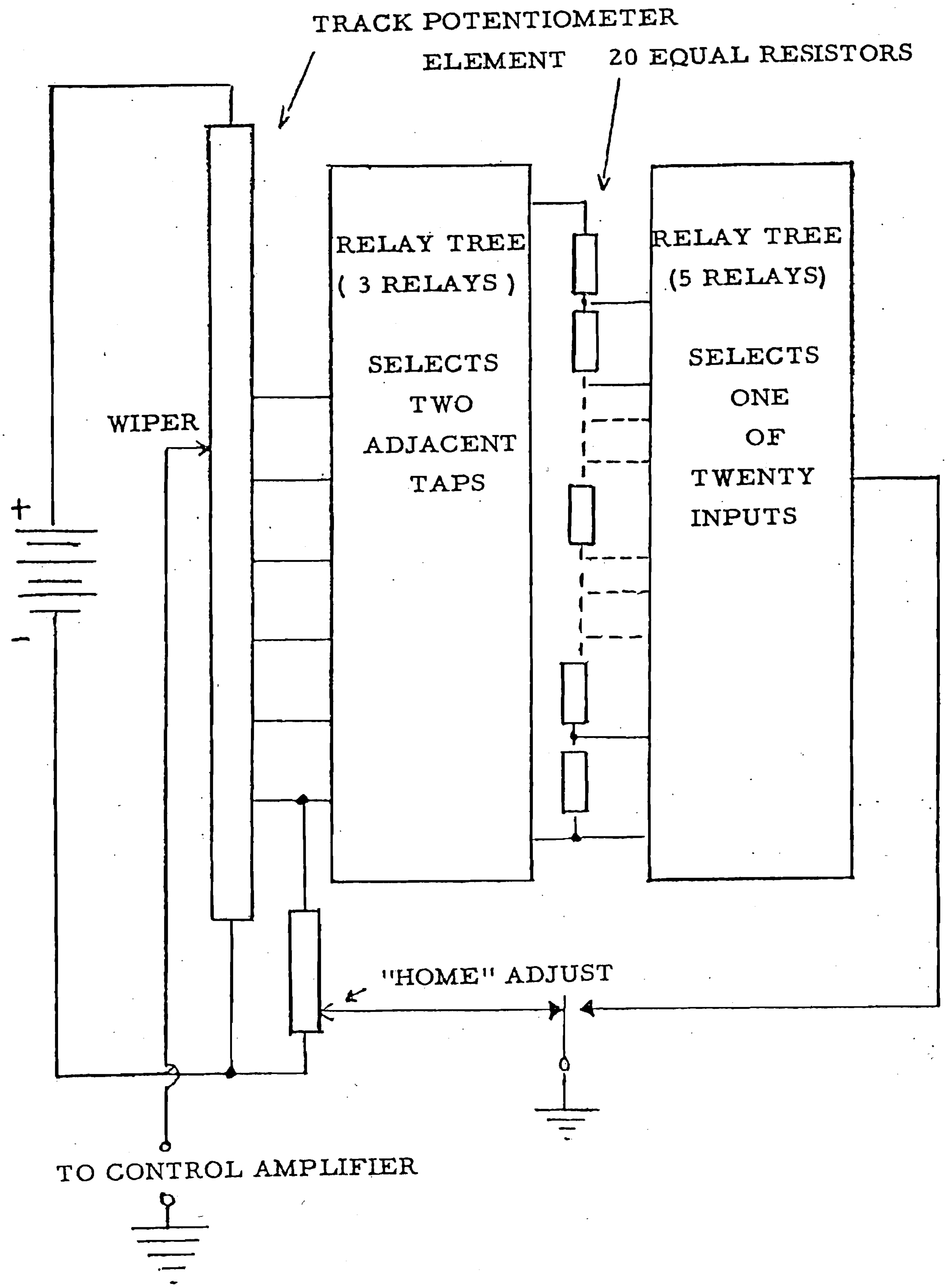
## The Relay - Addressing System

In both the disk and the track-addressing systems the method chosen permits the potentiometers used to have a lower linearity requirement than is required with untapped-potentiometer systems.

The disk potentiometer is made of a conductive-plastic strip which has fifty taps, one for each disk. The strip has its two end terminals connected to an electrically-floating d-c voltage source. One of the fifty taps is grounded through the points of the address relays. A wiper moves along this strip and is the positioning signal for disk drive. See Figure 2. When not at the grounded tap a voltage of about 2.5 volts per disk error is obtained. The exact voltage between taps is not critical since zero voltage is obtained at the desired disk by virtue of a precisely located tap. A moderate linearity of about five per cent is desirable from the control standpoint.




DISK ADDRESS SYSTEM


TRACK POTENTIOMETER
ELEMENT
20 EQUAL RESISTORS
RELAY TREE
( 3 RELAYS )
SELECTS
TWO
ADJACENT
TAPS
RELAY TREE
(5 RELAYS)
SELECTS
ONE
OF
TWENTY
INPUTS
WIPER
+
-
"HOME" ADJUST
TO CONTROL AMPLIFIER

The track potentiometer is arranged in a similar manner but it is not feasible, nor necessary, to have one-hundred taps to correspond to each of the track locations. Here instead, six taps are provided with the section between adjacent taps corresponding to twenty track positions. To select individual tracks, twenty equal, fixed resistors, in series, are connected across a pair of adjacent taps. The null position on the potentiometer is shifted along by grounding at one point along the twenty resistor chain. See Figure 3. This arrangement requires the potentiometer to have sufficient linearity between taps to indicate the position adequately, but relieves the overall linearity requirement by a factor of six from an untapped-potentiometer system. The gradient along this track potentiometer is about 1.2 volts per track.

In addition to the one-hundred track addresses there is one other address required on track drive. This is the position where the arm is fully retracted for travelling between disks called the "home" address. This position is established by a potentiometer connected between the tap corresponding to the outermost track and the end terminal of the potentiometer. See Figure 3. The track address or the "home" address is chosen by a transfer point on a relay which grounds either a point along the twenty-resistor chain or the wiper of the aforementioned potentiometer.

Control-System Logic

The control-system logic consists of a group of relays which, based on certain inputs, decide what actions need to be taken to position the heads to the selected address.

The general procedure followed was to set up all possible combinations of the input conditions, rule out all those which are mechanically prevented and define the actions to be taken for the remaining combinations.

The input conditions used are as follows:

A. Start signal from controlling source.

B. Disk detent engaged. (Arm free, carriage locked)

C. Disk detent disengaged. (Carriage free, arm locked in home position)

D. Disk null.

E. Track null.

F. Clutch power.

Both conditions of the disk detent are included since, although they are mutually exclusive, the disk detent may be between the two conditions.

The controlled relays are listed below:

A. Start relay

B. Disk-drive relay (negative = track drive).

C. Track-address relay (negative = home address).

D. Clutch-power relay.

E. Disk detent.

F. Arrival sequence.

The start relay is a key relay in the system. The disk-drive relay feeds the disk-position or the track-position error to the control amplifier; when disk driving the relay is picked, when track driving the relay is dropped. The track-address relay switches between the selected track address or the home-position address. The clutch-power relay interrupts power to the clutches. The disk detent is engaged by energizing a solenoid valve, the detent itself is pneumatic. The arrival sequence consists of removing clutch power, track detenting, putting the magnetic heads on the disk and after a suitable delay giving the ready signal to the machine using the 350.

The possible combinations of inputs and the action taken by the controlled relays will be listed separately on Figure 4.

The following listing gives conditions for a normal-access sequence. The actions to be taken are listed for each condition. These are the basis for the logic used in the control system.

1. Awaiting next command, start signal off.

   Ready for track drive.
   Disk detent engaged.
   Clutch power off.
   Track detent de-energized.

2. New address put into address relays.

   Home address chosen if new disk, if not, track address is chosen.

3. Start signal given (assume new disk addressed).

   Start relay picked.
   Disk detent de-energized.
   Clutch power on.

4. Arrival at home position and disk detent begins to disengage.

   Clutch power off.

5. Disk detent disengaged

   Disk drive chosen.
   Clutch power on.

6. Arrival at correct disk

   Track address chosen.
   Disk detent energized.
   Clutch power off.

7. Disk detent starts to engage

   Track drive chosen.

8. Disk detent engaged

   Clutch power on.

9. Arrival at the correct track

   Arrival sequence.

In addition to the normal sequence, provisions must be made to handle abnormal input combinations so as to route them into the normal sequence given above. These are indicated inFigure 4.

## CONTROL - SYSTEM LOGIC

| INPUTS | | | | | | CONTROLLED ACTIONS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| START | DISK DETENT ENGAGED | DISK DETENT DISENGAGED | DISK NULL | TRACK NULL | CLUTCH POWER | START RELAY | DISK-DRIVE RELAY | TRACK-ADD, RELAY | CLUTCH POWER RELAY | DISK DETENT SOLENOID | ARRIVAL SEQUENCE |
| A | B | C | D | E | F | a | b | c | d | e | f |
| 1 | 0 | 0 | 0 | x | x | 1 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 0 | 0 | x | x | 1 | 0 | 0 | 1 | 0 | 0 |
| 1 | 0 | 1 | 0 | x | x | 1 | 1 | 0 | 1 | 0 | 0 |
| 1 | 0 | 0 | 1 | x | x | 1 | 0 | 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 | 0 | x | 1 | 0 | 1 | 1 | 1 | 0 |
| 1 | 1 | 0 | 1 | 1 | x | 1 | 0 | 1 | 0 | 1 | 1 |
| 1 | 0 | 1 | 1 | x | x | 1 | 1 | 1 | 0 | 1 | 0 |
| 0 | x | x | x | x | 0 | 0 | x | x | x | 1 | 0 |
| 0 | 0 | 0 | 0 | x | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 0 | x | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | x | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 1 | x | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | x | 1 | 1 | 1 | 1 | 0 | 1 | 0 |

SYMBOLS

1 - OPERATE

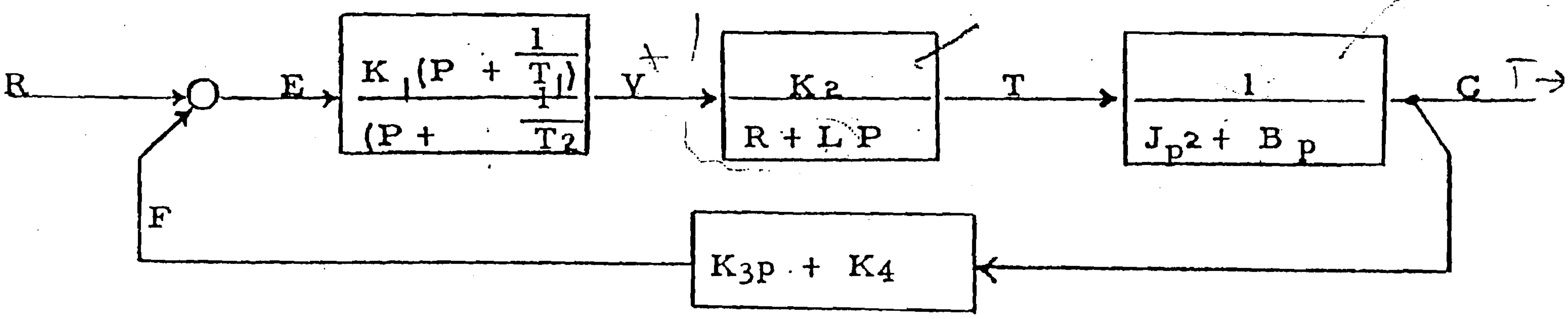
0 - DON'T OPERATE

x - DON' T CARE

## Control - System Dynamics

A rigorous analysis of the control-system dynamics will not be made because nearly every component in the feedback loop has some non-linearity and at least one nonlinear element has been added. However, an approximate linear analysis gives some insight into the dynamic behavior. A description of the use of position-error limiting shows how differences in clutch characteristics can be compensated.

The linear analysis will use root-locus techniques. * The block diagram below represents the feedback-control system over the frequency range of interest.




Each of these blocks will be discussed before continuing with the analysis. The letter "p" in each block represents the complex-frequency variable, $\sigma + j\omega$.

The amplifier block has a non-frequency-sensitive term, $K_1$, which is the d-c voltage gain of the amplifier. The value of $K_1$ depends upon the size of the error voltage, but it is about 400 near zero input. The two time-constants, $T_1$ and $T_2$, represent the effect of an R-C network in the amplifier.

The constant, $K_2$, represents the torque-to-current ratio for the clutch, which for the coil we use is about 400 inch-pounds per ampere. $R + L_p$ represents the impedance of the coil.

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* See Control-System Dynamics by W. R. Evans, McGraw-Hill, 1954

This block has voltage input and torque output.

The inertia term is made up of the inertia of the load and of the clutch-output shaft. It has a value near 3.5 pound-inch$^2$. A viscous-damping (resisting torque proportional to angular velocity) term is added, representing the torque to velocity ratio. A value of 0.27 inch-pound-second per radian is used for B. This block has torque input and angle output.

The tachometer and potentiometer terms are adjustable and differ for track and disk drives. $K_3$ has a maximum value of 0.36 volt-sec per radian and $K_4$ has 25 volts per radian for track and 7.5 volts per radian for disk drive. This block converts angle to voltage.

The closed-loop transfer function is expressed as:

$$\frac{C}{R}(p) = \frac{K_1 K_2 (p + \frac{1}{T_1})}{LJp\,(p + \frac{1}{T_2})(p + \frac{1}{T_4})(p + \frac{1}{T_5}) + K_1 K_2 K_3 (p + \frac{1}{T_1})(p + \frac{1}{T_3})}$$

Where time-constant substitutions have been made as follows:

$T_3$ represents the ratio $K_3/K_4$

$T_4$ represents the ratio $L/R$

$T_5$ represents the ratio $J/B$

The zero of equation 10 occurs when $p = \frac{-1}{T_1}$. To find the poles, root-locus techniques will be used. The denominator is rewritten in a suitable form for root-locus analysis.

$$D = K_1 K_2 K_3 \left(p + \frac{1}{T_1}\right)\left(p + \frac{1}{T_3}\right) \left[ \frac{LJ\, p \left(p + \frac{1}{T_2}\right)\left(p + \frac{1}{T_4}\right)\left(p + \frac{1}{T_5}\right)}{K_1 K_2 K_3 \left(p + \frac{1}{T_1}\right)\left(p + \frac{1}{T_3}\right)} + 1 \right] \qquad (11)$$

The complex-frequencies, p, which make the bracketted term zero, are the poles of equation 10. (At these frequencies, an output is obtained for zero input.) Lumping all the non-frequency-sensitive terms into $M = LJ/K_1 - K_2 - K_3$ and re-writing the bracketted term only.

$$Y = \frac{M\, p \left(p + \frac{1}{T_2}\right)\left(p + \frac{1}{T_4}\right)\left(p + \frac{1}{T_5}\right)}{\left(p + \frac{1}{T_1}\right)\left(p + \frac{1}{T_3}\right)} + 1 \qquad (12)$$

or

$$\frac{M\, P \left(p + \frac{1}{T_2}\right)\left(p + \frac{1}{T_4}\right)\left(p + \frac{1}{T_5}\right)}{\left(p + \frac{1}{T_1}\right)\left(p + \frac{1}{T_3}\right)} = |1| \angle 180^\circ \qquad (13)$$

As M varies from zero to infinity a locus of roots, (values of p) which satisfy equation 13, can be traced on the p-plane. The root-locus technique solves (13) by finding the values of p which satisfy the angle criterion first, then values of p on these loci which satisfy the gain term, M. Because $T_3$ can be set at a range of values the effect of various varying $T_3$ will be shown by a series of root-locus sketches, see Figures 5, 6 and 7.

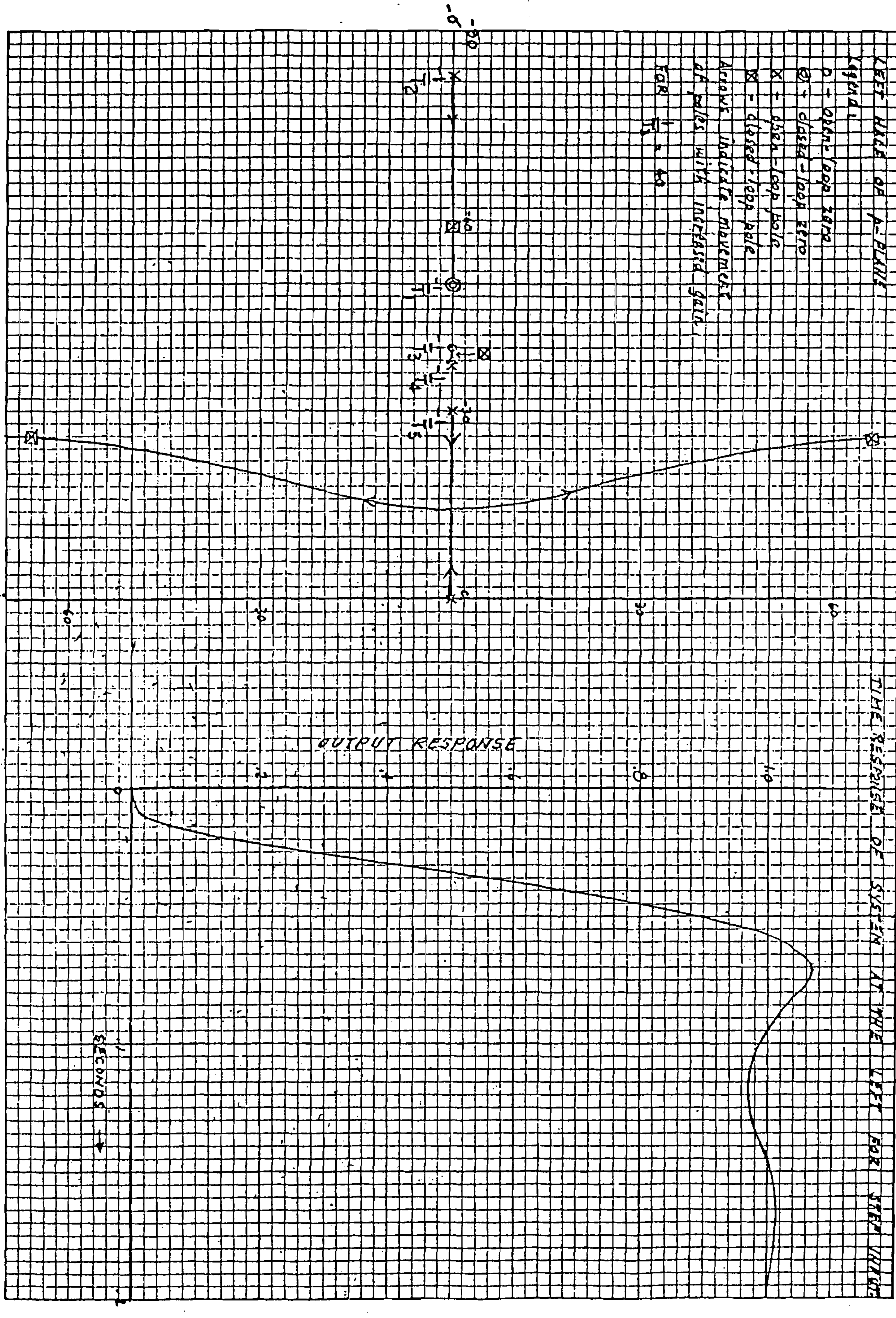


FIGURE 5;

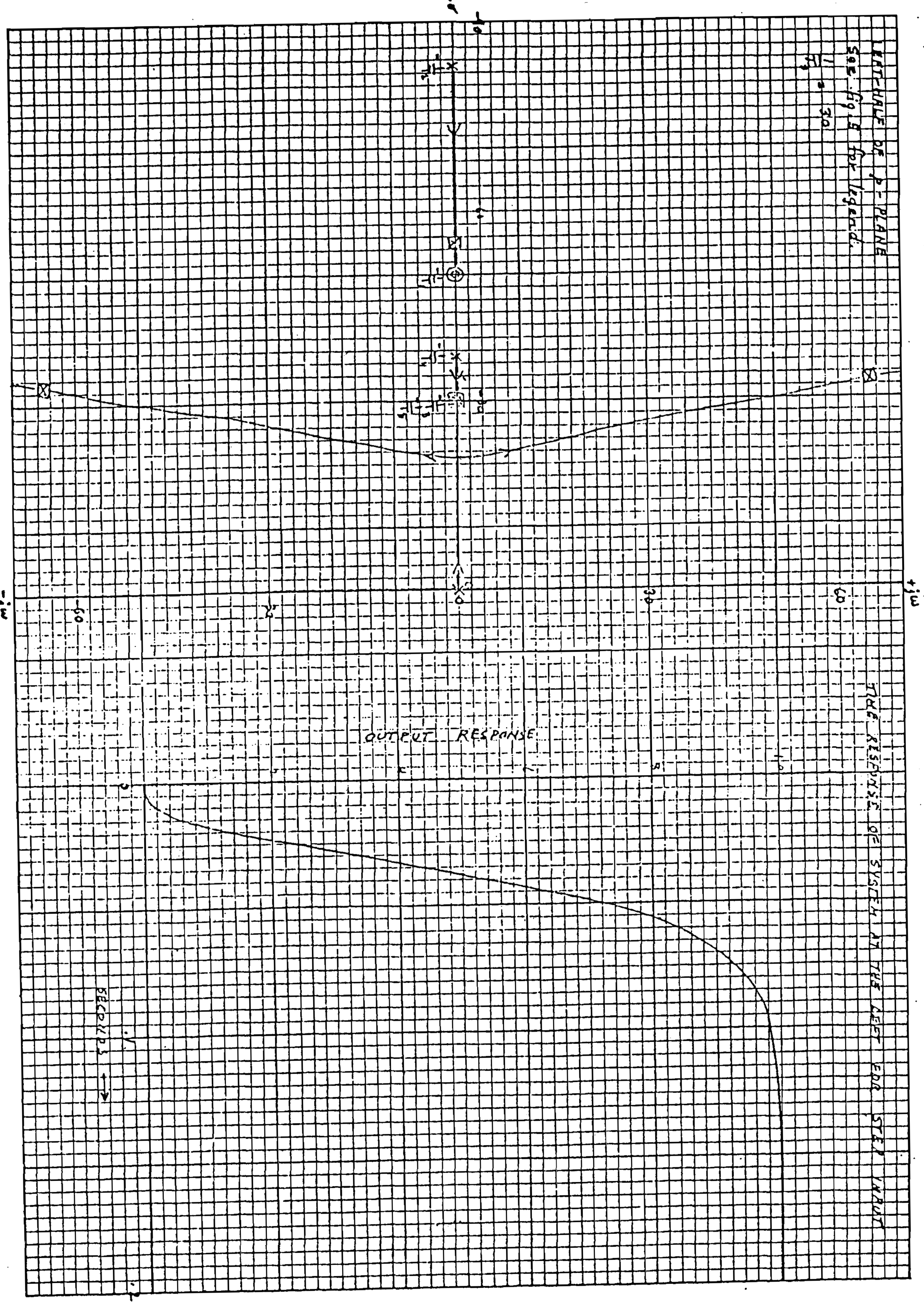


FIGURE 6

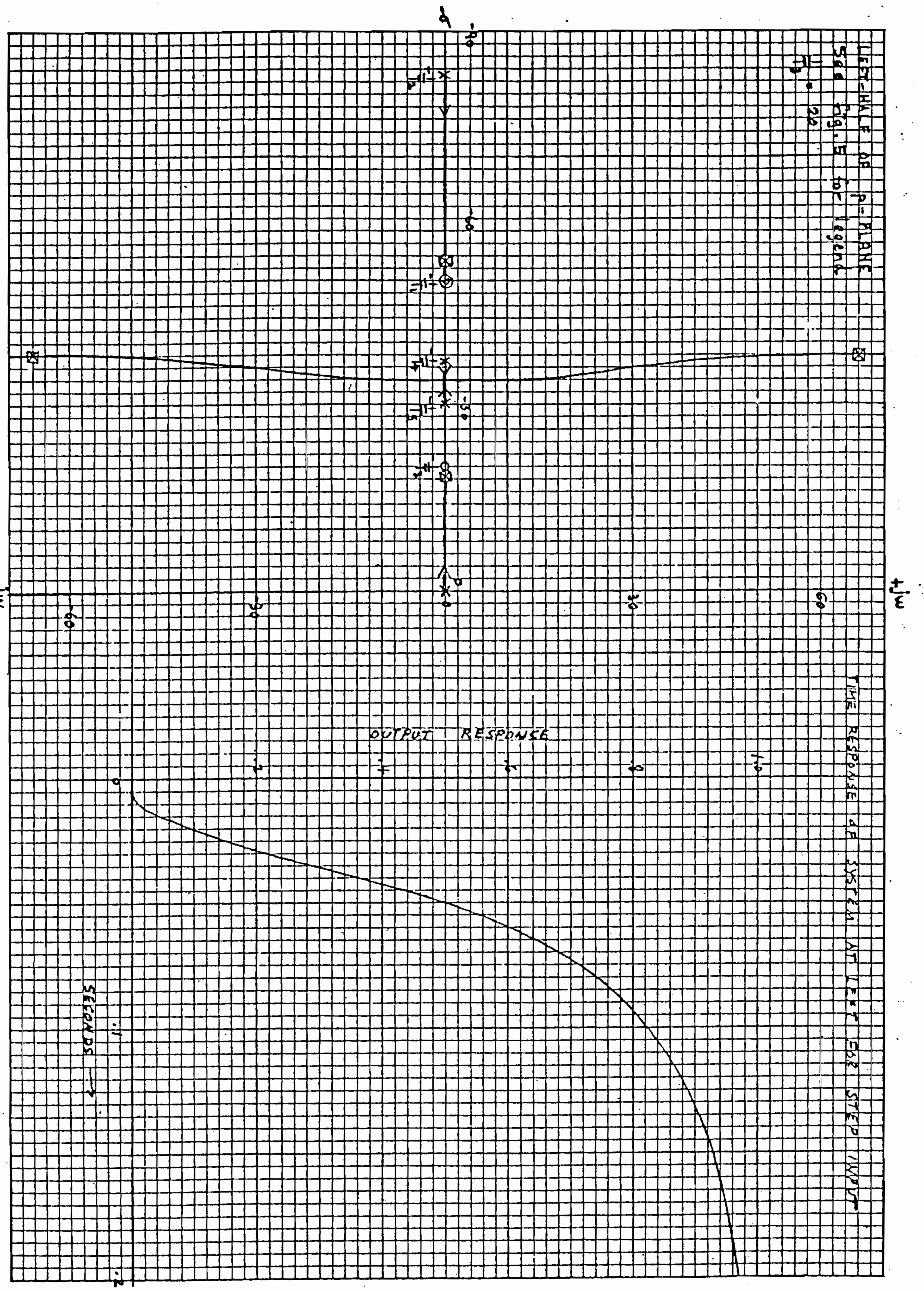
LEFT-HALF OF P-PLANE
See fig. 5 for legend
-jω
+jω
TIME RESPONSE OF SYSTEM AT LEFT FOR STEP INPUT
OUTPUT RESPONSE
SECONDS

FIGURE 7.

In these plots $1/T_3$ is assigned values of -40, -30 and -20. For these values one real pole of the closed-loop transfer function varies from -59 to -53, the other real pole stays with $-1/T_3$ going from -39 to -19. The complex poles vary from a damping ratio of 0.37 to about 0.5 at a natural frequency of about 10 cycles per second. The significance of the location of poles and zeros is considered in the literature. The general expression for the time response of the above system to a step input can be expressed as:

$$C(t) = A_0 + A_1 \epsilon^{-p_1 t} + A_2 \epsilon^{-p_2 t} + A_3 \epsilon^{-p_3 t} \sin(wt + \phi) \quad (14)$$

The responses for the three pole-and-zero configurations are shown in the accompanying time-response curves on Figures 5, 6 and 7. These curves obviously hold only for the short travel where the overall system is linear.

Because of the way this controller operates it is very similar to the operation of an "on-off" controller. (The only difference is that here the controller has a proportional region to operate in for small error signals.) With this type of controller it is necessary to determine the switching time.* Because the plot of error versus error rate is nearly a parabola, an attempt was made to achieve this curve in this controller by use of a controlled limiter. This limiter distorts the error voltage versus error curve so as to approximate the parabolic-switching curve. By using separate limiter controls for the two polarities of position error, an independent adjustment is provided to compensate for the differences between magnetic clutches. This adjustment is provided as a means of obtaining the desired performance and yet to allow a wide tolerance in the clutch, torque-current characteristics.

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* A very applicable article is: "Some Design Considerations of a Saturating Servomechanism." by P. E. Kendall and J. F. Marquardt Proc. Nat'l. Elec. Conference Vol. IX.

Start.