AN INVESTIGATION OF THE EFFECTS OF THE VARIATION OF HEEL GAP ON THE PERFORMANCE OF ELECTRO-MECHANICAL RELAYS

By

CHARLES C. MACK

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

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PREFACE

Research into the factors which govern the operation of electromechanical relays has been intensified within the last decade or two. This has resulted mainly from the increased need for reliability, consistency and maintenance of certain operating characteristics within prescribed limits in the application of these relays to control systems of industrial, commercial and military equipment. Although much research work has been done on the factors which affect the operating characteristics of the electromechanical relay, apparently very little has been done on the effect of variation of the heel gap on the performance of electromechanical relays. The meager information available in this area prompted the author to carry out the necessary research and submit a thesis on this subject.

In conducting research on electromechanical relays the author soon discovered that one of the greatest problems arose from the difficulty in obtaining complete data during each operation of the relay. Mechanical binding or friction tends to cause a deviation of the data during successive operations of the relay when the mechanical adjustments and the applied step voltage remains constant. It therefore becomes necessary that the transient current and the armature motion time be recorded simultaneously. This was accomplished in the recording of data for the second relay which was used and the method for accomplishing this is described in the thesis.

As a result of the analysis of the data and the ultimate hypothesis that there was an analogy between the armature motion time and the energy in the pure inductance part of the circuit, the need for instrumentation which would permit measurement of the product of voltage and current in the inductance during the transient period was realized. A scheme which may accomplish this is mentioned in the thesis. The time limitation prevented design and construction of the necessary equipment for use in carrying out the experimental instantaneous power measurements.

Acknowledgement and appreciation to Professor Charles F. Cameron, Acting Head of the Electrical Engineering Department of Oklahoma State University is hereby expressed for the guidance and assistance which he so generously contributed in carrying out the research work and the writing of this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

Figure		Page

CHAPTER I

BACKGROUND INFORMATION

Relays are now used in vast amounts throughout industry, in military equipment, and within the home. For many years after electromechanical relays were first developed, they were used almost exclusively to close or interrupt an electrical circuit without consideration to such items as the speed of operation, consistency of successive operations, transient characteristics and other such factors. More recently, however, newer, more complex and sophisticated electrical devices require that consideration be given to nearly all factors which affect electromechanical relay performance. Complicated and sensitive associated electrical circuitry requires that consideration be given to the interference that might arise from the electrical transients which exist as the result of relay operation. Requirements for high speed communications have imposed a greater demand for relays capable of rapid and reliable operation. In many instances successful operation of controls, guidance systems and power plants of military and research missiles depend on the operation of relays.

General Progress on Relay Research

Only in recent years has much been done in the way of coordinated research on the factors which influence the operation of electro-mechanical relays. This has largely been accomplished through the banding together of interested groups into the National Association of Relay Manufacturers.

This Association in recent years has compiled information in the form of papers submitted by individuals from all over the world at the annual meetings of the Association.

Because of the large number of the variables which are involved with the operation of a relay, much of the information obtained has been determined through experimental means with little exact correlation with mathematical analysis. Usable mathematical procedures for analysis of relay operation have been difficult, and in many cases impossible, to attain. In some instances empirical formulas for determining limited operating information for certain relays have been obtained by correlation with experimental data. Although considerable research has been conducted as outlined above, the author of this document is not aware of any work having been done on the Effect of the Variation of Heel Gap on relay performance.

General Characteristics of Relays

The average relay consists of a magnetic circuit with a coil wrapped around some part of it to introduce the driving mmf and create the flux within the magnetic circuit. Part of the magnetic circuit consists of an armature which is fixed at one end in space but permitted to pivot about a hinge. The other end is free to move over the path of an air gap, which is a variable part of the magnetic circuit. (See Fig. 1 for a diagram of a simple relay.)

The magnetization curve of the ferromagnetic material which is used in the magnetic circuit of the relay plays an important part in its operation. Rapid and linear increase in flux density B with increase in magnetic field intersity H are desirable characteristics of the material for

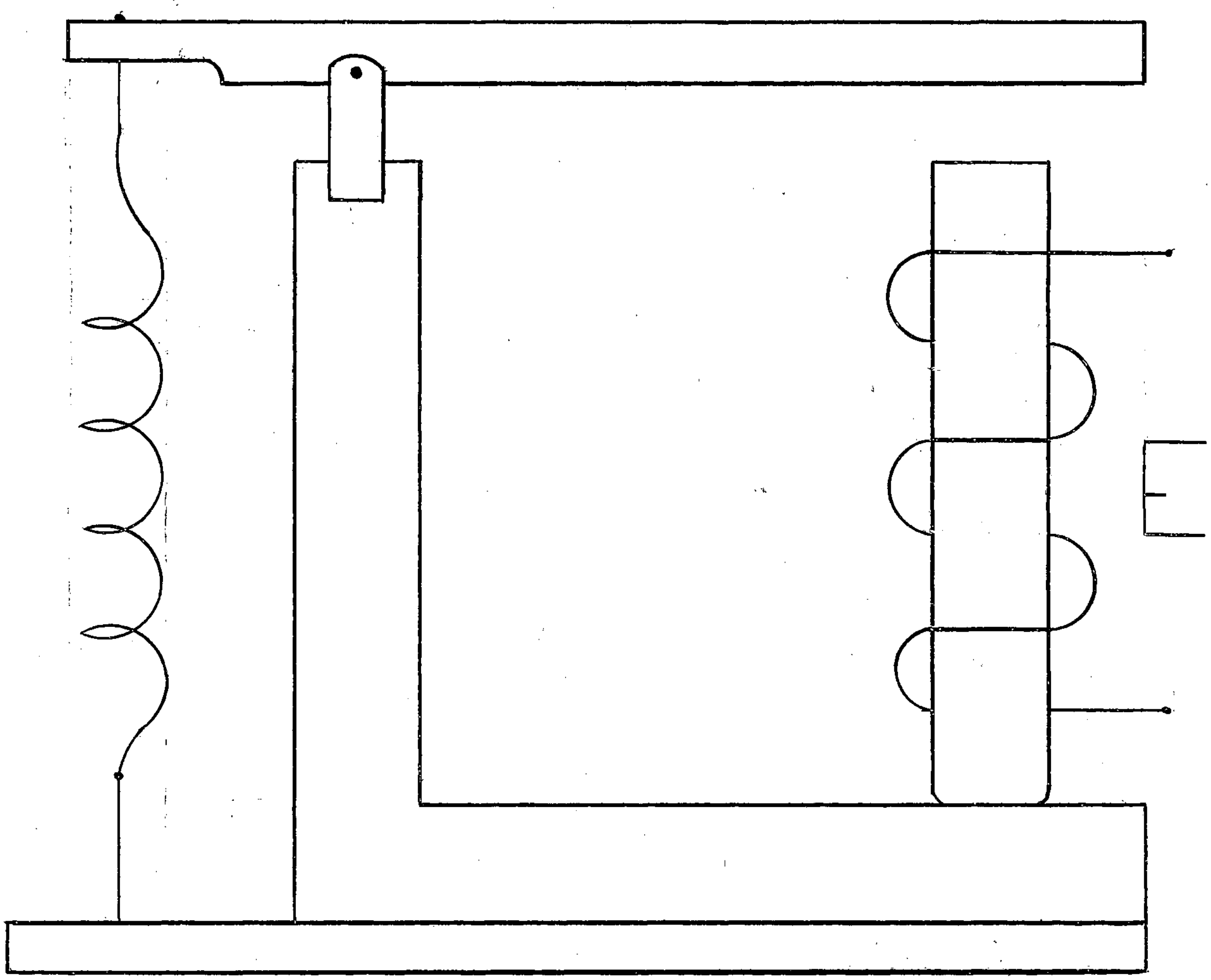


Fig. 1. Diagram of a Simple Relay

most relays. For this reason soft ferromagnetic materials and alloys which exhibit these characteristics are most often used in the construction of the magnetic circuit of relays. (See Fig. 2 for relative comparison of the hysteresis loops of soft and hard materials.) From the figure we can readily see that if rapid operation of the relay is desired (and this would seem to be the usual case) then they should be designed to operate on the more linear portion of the BH curve. This gives a constant μ since it is equal to B/H.

If the change in slope at the very early portion of the BH curve is disregarded, a constant inductance for the circuit can be assumed for certain portions of the relay transient period. This introduces little error and permits simplified calculations for certain portions of the transient period because the relay coil and magnetic circuit can be treated as a simple RL circuit.

The transient current in the relay can be divided into three distinct periods (see Fig. 3). At t = 0 a step voltage is applied to the relay terminals. The current buildup is that for a simple RL circuit until the attractive force across the armature air gap, which is created by the increasing flux, becomes great enough to overcome the spring tension on the armature. This completes the first period, and the current with respect to time during this period can be analyzed by conventional methods as follows:

Kirchoff's voltage equation is

$$E = L\frac{di}{dt} + Ri = L\left(\frac{d}{dt} i_{ss} + \frac{d}{dt} i_{tr}\right) + R(i_{ss} + i_{tr}).$$

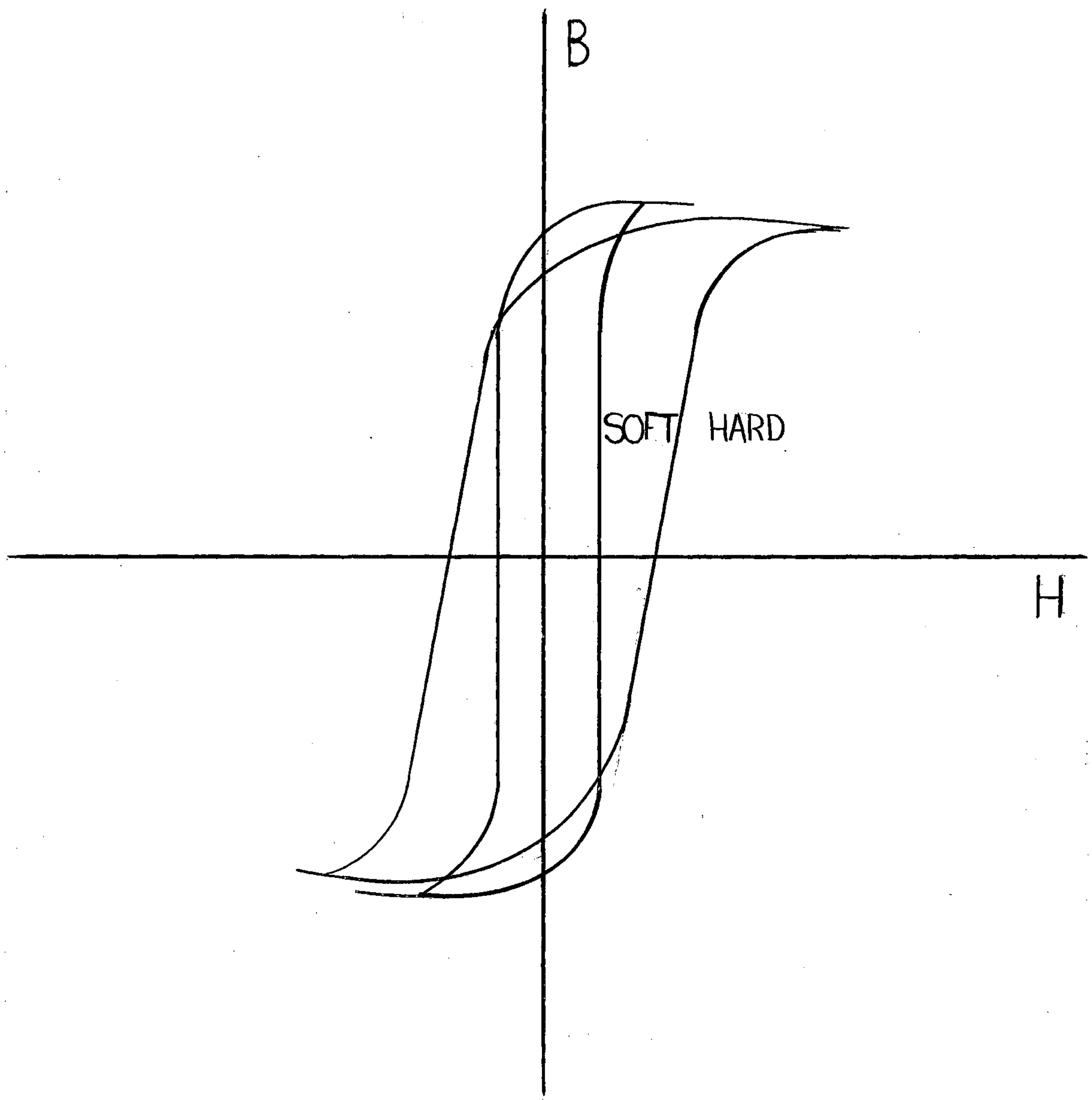


Fig. 2. Relative Comparison of Hysteresis Loops of Soft and Hard Materials

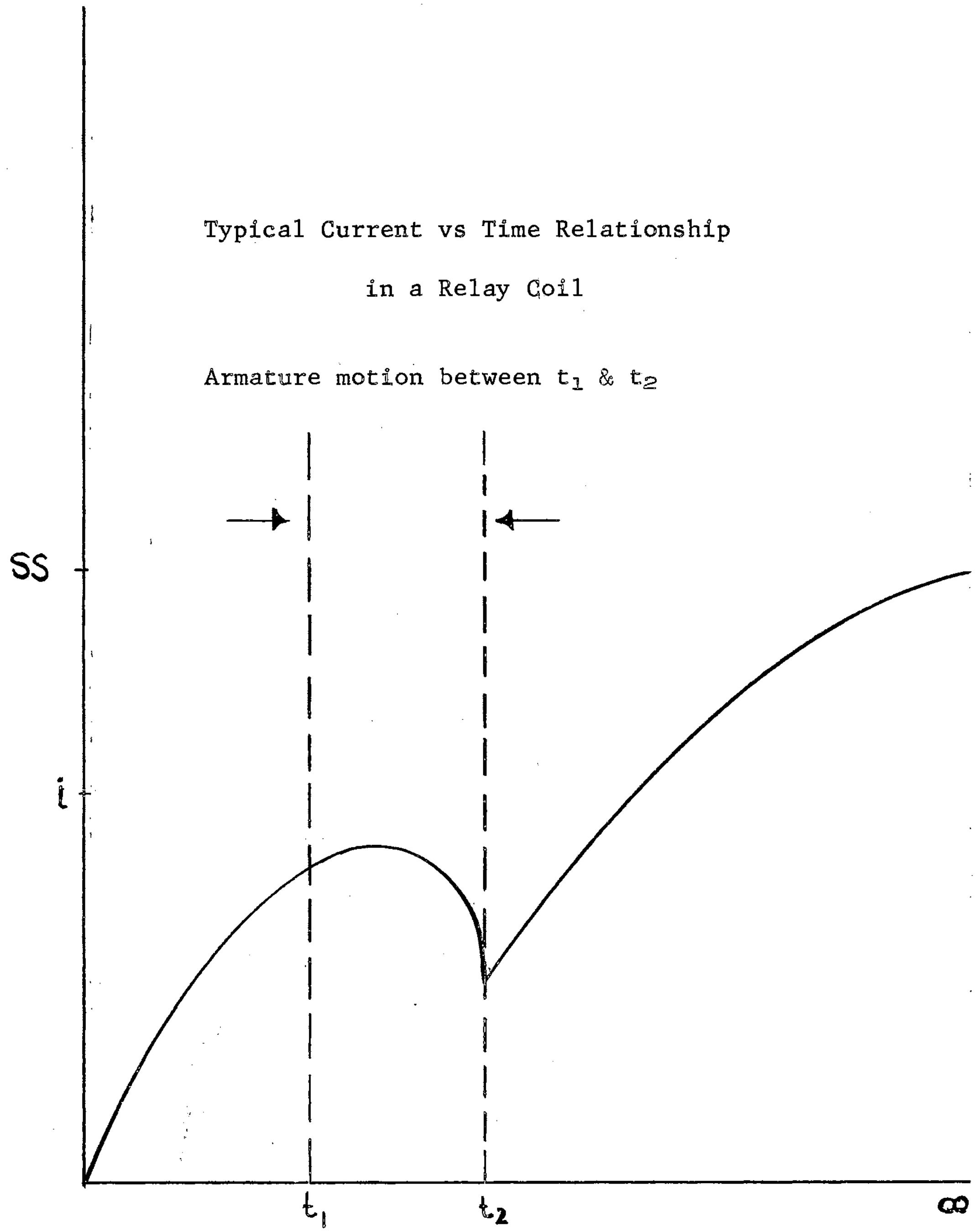


Fig. 3. Transient Current Curve During Operation of a Simple Relay

When steady state conditions are reached,

$$\frac{d}{dt} i_{ss} = 0$$

and at this condition when t = infinity all of the voltage appears across the R, and then the above equation becomes

$$E = L \frac{d}{dt} i_{tr} + R \left(\frac{E}{R}\right) + Ri_{tr}.$$

Solving this equation gives

$$0 = L \frac{d}{dt} i_{tr} + Ri_{tr}.$$

To solve this equation, assume $i = Ae^{st}$ and $\frac{di}{dt} = sAe^{st}$,

then $0 = LsAe^{st} + RAe^{st}$ and $s = -\frac{R}{L}$.

The total current can now be expressed as

$$i = i_{ss} + i_{tr}$$

or

$$i = \frac{E}{R} + Ae^{-Rt/L}.$$

By evaluating A at t = 0 when we know that i = 0,

$$A = -\frac{E}{R}.$$

By substituting into the previous equation

$$i = \frac{E}{R} (1 - e^{-Rt/L}). \qquad (1)$$

After the flux in the magnetic circuit has built up sufficiently to create enough force on the movable armature to cause it to just start to move (t_1 on Fig. 3), and until the armature completes its motion (t_2 on Fig. 3), an entirely different condition exists. The armature motion causes a change in the air gap, which in turn causes a change in the reluctance and introduces another variable. The change in this variable is determined by the magnetomotive forces present in the magnetic circuit and the change of flux as well as the gap in the armature circuit. The magnetomotive forces and the change in flux as the result of armature gap are dependent upon one another. The magnetomotive forces affect the change in flux, and the change in flux affects the current and therefore the magnetomotive force. Since $e = -N\frac{d\phi}{dt}$, any change in flux as the result of armature motion will create a counter emf to the applied step voltage and consequently reduce the current in the relay coil. In addition to the above factors, the rate of change of flux in the armature circuit is also affected by the mechanical size and configuration of the armature circuit, spring tension, linkage and possibly other factors. It can therefore be seen that the transient period where the armature motion takes place is very difficult to evaluate, and most of the information can be readily obtained only through experimental means.

From t_3 until μ is no longer constant, the current and attendant flux variation can again be evaluated as was done for the first period with provision made for the $i(0)$ which will exist at the end of the armature motion.

CHAPTER II

THE MAGNETIC CIRCUIT

The magnetic circuit is of prime importance among the factors which affect the operation of the electromechanical relay. It is this part of the mechanism which stores the energy introduced by the primary power source as the driving mmf in the relay coil and which provides the force that actuates the realy. It is therefore necessary for some time to elapse before the flux density reaches a sufficient value for the required force to be attained. The equation for the attractive force on the armature is:

$$F = \frac{B^2 A}{2\mu_o} \tag{2}$$

Where F = Force in newtons

B = Flux density (webers/meters^2)

A = Area

μ_o = Permeability for air

After $t = 0$, the current in the relay coil continues to increase until the flux density B reaches a sufficient value to overcome the spring tension and the armature begins to move. As the armature moves towards the pole face, the air gap approaches zero value and reduces the reluctance of the magnetic circuit. This causes a rapid change in flux within the magnetic circuit.

Since:

$$E = iR + N\, d\phi/dt \tag{3}$$

this change in flux causes a greatly increased induced emf over that for a simple RL circuit, and this induced or counter emf causes a drop in the relay coil current. This drop in relay coil current is characteristic for all general relay operation, and the typical current vs time curve is shown on Fig. 3. Since armature movement requires an expenditure of energy and therefore a transfer of energy from the magnetic circuit, the current change might be considered as an indicator of this energy transfer. Although this current drop which takes place during the armature motion may be an indicator of energy transfer, it does not directly indicate the degree of energy existing in the inductive circuit or magnetic field. The energy in a pure inductance is the product of the current through and the voltage across the inductance integrated over the time.

In understanding the storage and transfer of energy within magnetic fields, the following relationships are helpful:

$$Wf = \frac{B^2 \ A \ lf}{2\mu f} \qquad (3)$$

$$Wa = \frac{B^2 \ A \ la}{2\mu o} \qquad (4)$$

$$Wt = \int_o^t p \ dt = \int_o^t e_L \ i_L \ dt = \frac{Li^2}{2} \qquad (5)$$

Where

Wf = Energy (joules) in ferromagnetic material

Wa = Energy (joules) in the air gap

Wt = Energy (joules) total

lf = Length of ferromagnetic path

la = Length of air gap

A = Cross sectional area

μf = Permeability of ferromagnetic material

μo = Permeability of air

From the above relationships, it can be seen that:

$$Wt = Wa + Wf = \frac{B^2 A}{2} \left(\frac{lf}{\mu f} + \frac{la}{\mu o}\right). \qquad (6)$$

And when B is constant and la $\doteq$ 0, the Wt reduces in value and

$Wt = Wf$.

Because of the decreased current during armature operation, it is obvious that the induced emf in the coil becomes greater.

Since:

$$e_L = N\, d\phi/dt, \qquad (7)$$

it becomes apparent that the flux density must increase for the current to drop. It can be seen from the above described relationships that in all practical situations, the energy in the air gap will be divided between the ferromagnetic portion of the circuit and the energy required to operate the armature. The total energy in the magnetic field will be reduced, but the energy in the ferromagnetic portion of the magnetic circuit will increase to meet the new total energy value. Thus the energy in the air gap will not all be transferred to the mechanical energy. It can also be seen that for an armature of a mass approaching zero and spring tension approaching zero, then the operate time would approach zero and the energy used to operate the armature would approach zero. Under these conditions the energy in the air gap as the armature closed would flow into the ferromagnetic portion of the circuit and the total energy would remain the same. Under these same conditions the induced emf and current product would remain the same, with the induced emf increasing and the current decreasing.

From the previous discussion it is apparent that for a particular magnetic circuit and spring tension there is a certain value of flux required for the armature to start to move, and this is when the attractive force on the armature exceeds the spring tension. Before the armature starts to move and after it completes its motion, the inductance can be computed for the particular magnetic circuit for the portion of the BH curve where the μ is somewhat constant, as follows:

Since:

$$e_L \doteq L\, di/dt = N\, d\phi/dt \tag{8}$$

Then:

$$L = \frac{N\phi}{I} \quad . \tag{9}$$

Although some authors attempt to explain the armature motion conditions by computing effective inductance during this period, it should be remembered that this does not indicate true inductance of the fixed coil and magnetic parameters, but is caused by the change in flux which results from mechanical motion of the armature. It should also be remembered that the energy in the magnetic field of a pure inductance is the product of the current passing through and the voltage across the inductance integrated over the time from t = 0 until steady state conditions are reached. This is true regardless of what the value of inductance is at any time.

There are two other interesting relationships which should be discussed in futhering the understanding of the magnetic circuit of the electromagnetic relay. These are the current vs time characteristics for the relay which has its armature first blocked closed, then open, and then free to move; and the flux vs time relationships for similar conditions.

In the current vs time relationships (see Fig. 4), the three curves terminate at the same steady state conditions which are established by the

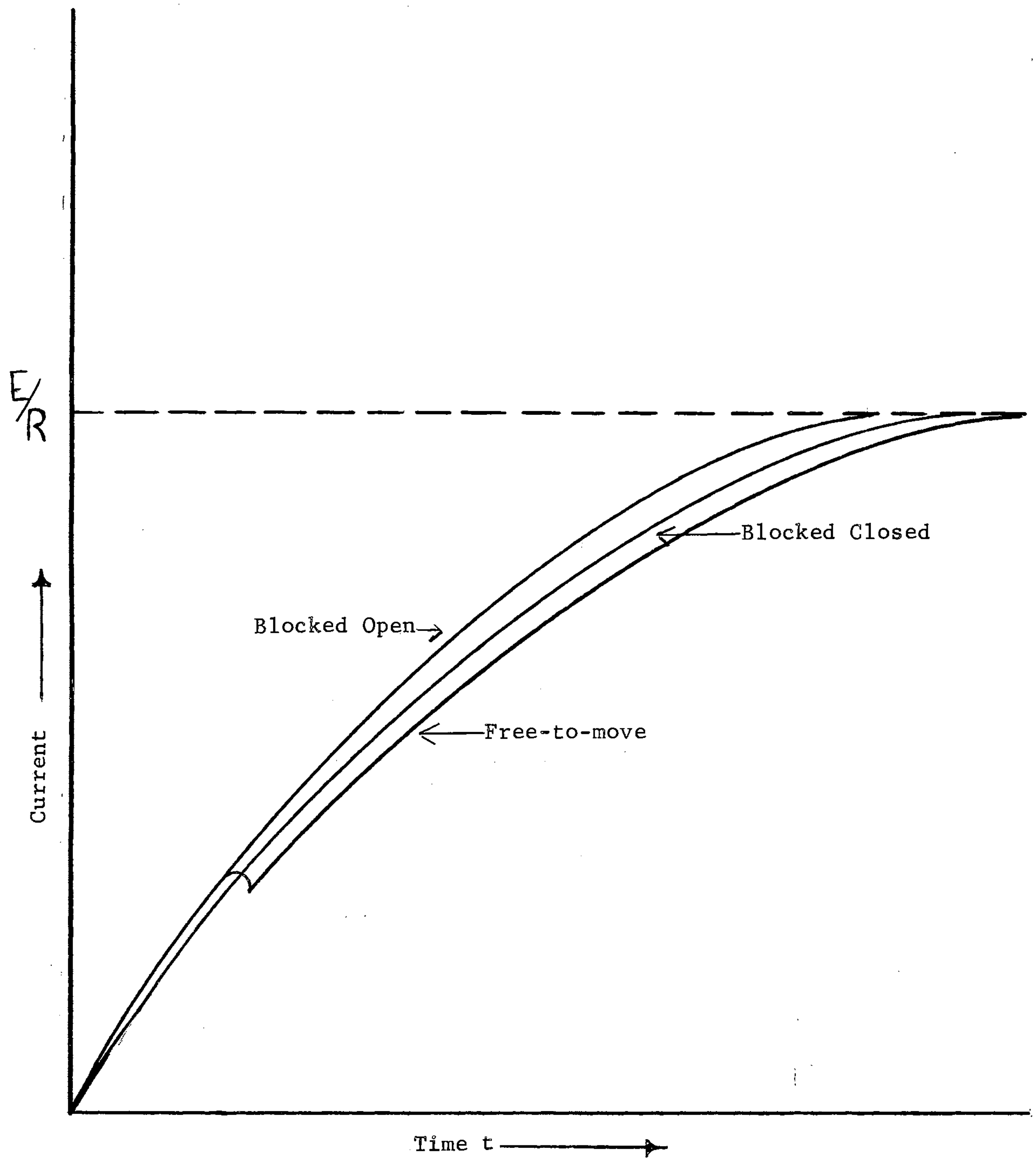


Fig. 4. A Typical Current vs Time Curve for Blocked Open, Blocked Closed, and Free-to-Move Conditions

value of E/R. The steady state conditions are reached more rapidly by the blocked open curve because the induced counter emf is less during the transient period. This is readily evident when the increased reluctance of the circuit under these conditions is considered. The free-to-move curve displays a typical curve showing the change in current as the armature motion takes place. It will be noted that after the armature motion is completed the build-up to steady state conditions is always longer in time than for the other two curves (blocked). The degree of displacement of the free-to-move curve from the blocked closed curve is primarily dependent on the mass of the armature and its spring tension. Greater spring tensions and armature masses required greater armature operate times because of the greater energy required. This increased armature motion time causes the portion of the free-to-move curve which occurs after armature motion has been completed, to be displaced further in time from the blocked closed curve. Again consider an armature of negligible mass and the spring tension immediately going to zero after the armature motion starts. During such a situation the current would go from the blocked open curve to the corresponding value of current on the blocked closed curve for the identical moment in time. No energy would be consumed, and the current voltage product of the inductance would remain constant. In order for the product to remain constant, the voltage across the inductance would have to increase to compensate for the decrease in the current.

In determining the changes in flux which occur during the operation of an electromechanical relay, the flux vs current curves for both the blocked closed and blocked open conditions should be reviewed (see Fig. 5). The curves shown are typical, and it should be noted that the two curves do not meet at some value of current where steady state conditions are

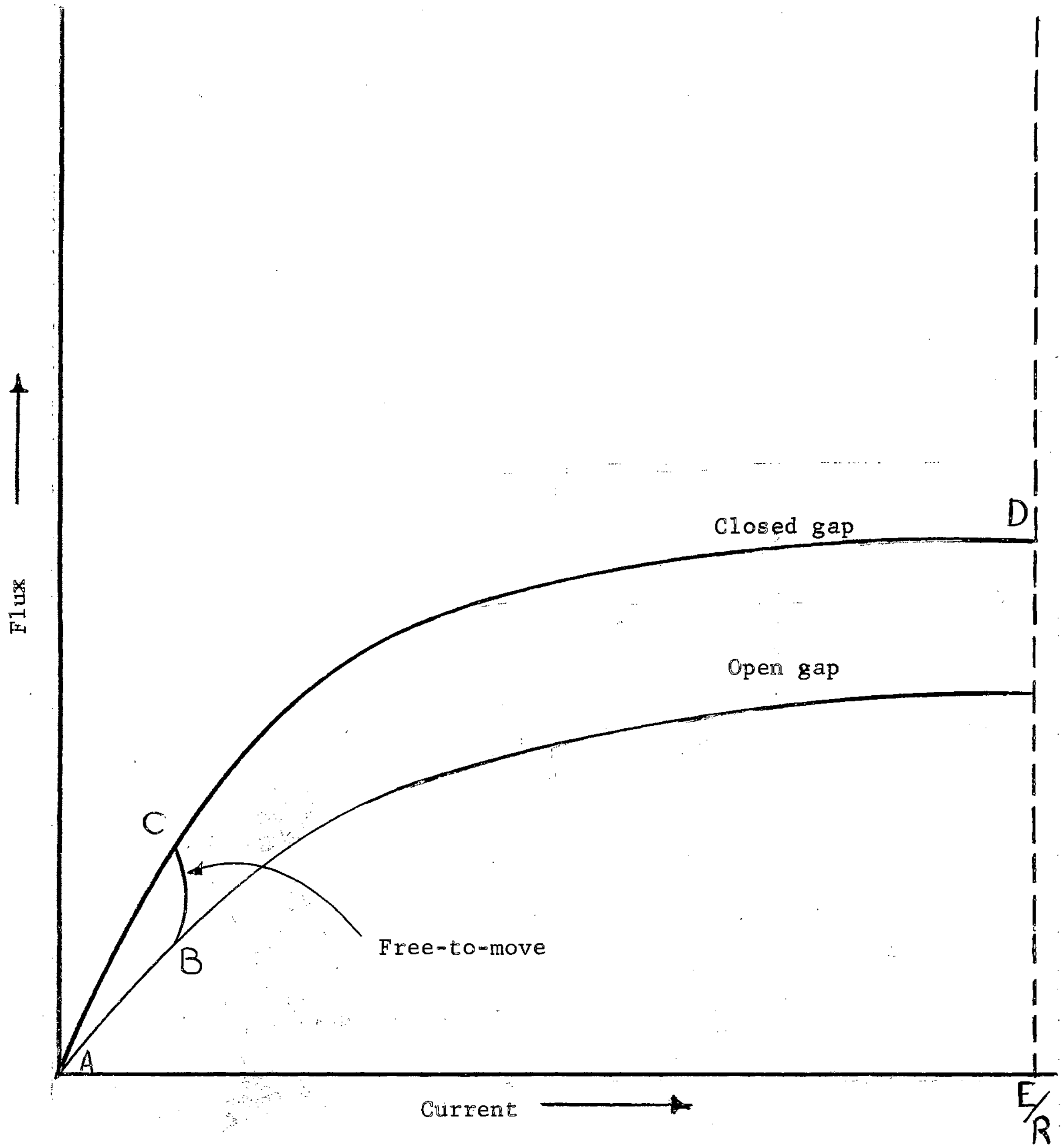


Fig. 5. A Typical Flux vs Current Curve for Blocked Open, Blocked Closed and Free-to-Move Conditions

attained. These curves do not converge because of the difference in reluctance with the same steady state current for both conditions. The free-to-move flux vs current curve passes through points ABCD of Fig. 5. Both the blocked open and blocked closed flux curves, as plotted, would be quite similar to curves plotted against time, since current under these conditions is increasing with time. The free-to-move flux curve represents the change in flux with change in current, and since the current cusp occurs later in time after the armature movement has once started, this curve as shown on Fig. 5 does not reflect the change in flux with respect to time during the armature motion time.

By referring to Fig. 6, the flux change with respect to time for the blocked closed, blocked open, and free-to-move conditions can be seen. The free-to-move curve is an estimate of the change of flux conditions with respect to time since, to the authors knowledge, no accurate flux measurements during armature motion have ever been made. Since steady state current will be reached at different times with the different reluctance conditions, the steady state flux positions are also reached at different times as indicated on the figure. The open gap, which has the most reluctance, reaches steady state current first, and with the closed gap condition steady state current is reached later in time. The free-to-move flux curve which is shown results from the reduced current during armature motion which causes the flux curve to be displaced later in time from the blocked closed curve. The portion of the curve which is representative of the conditions after the armature motion is completed is exactly the same as the corresponding portion of the blocked closed curve.

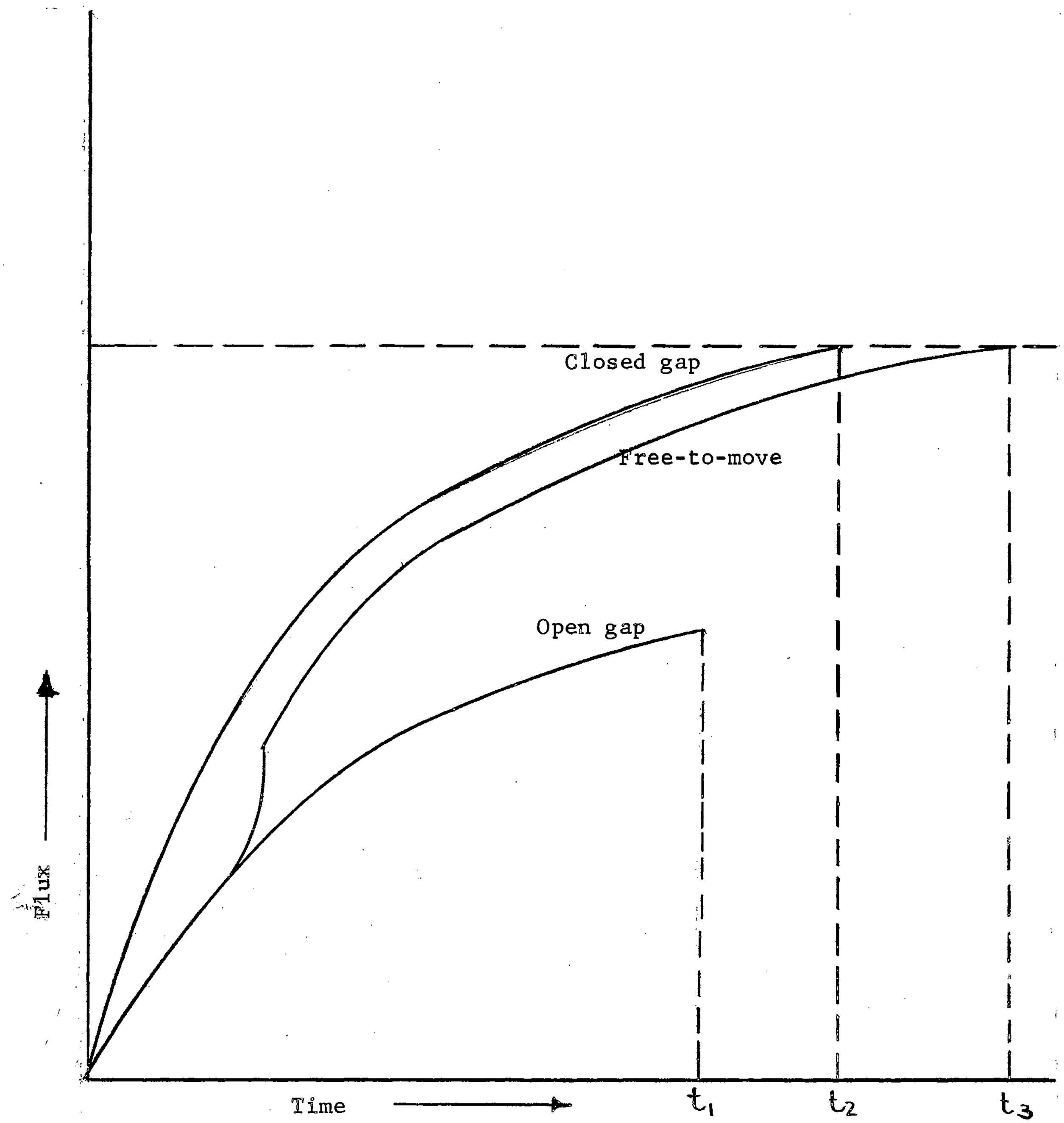


Fig. 6. A Typical Flux vs Time Curve for Blocked Open, Blocked Closed and Free-to-Move Conditions

CHAPTER III

A DESCRIPTION OF THE PROBLEM

In determining what effect the heel gap variation has on the performance of electromechanical relays, it becomes immediately apparent that any experimental arrangement which is used to obtain necessary data must include facilities for comparing this factor with the other variables having a bearing on the relay performance. These three factors (heel gap, spring tension, and armature air gap), all of which are variables, serve to complicate the process for obtaining the data and ultimately systematizing the results for application to other relays. In evaluating the overall problem, some attempt must be made to divide the areas of consideration so that the investigation can be systematized. In this instance these areas were to consist of two general divisions -- electrical and mechanical considerations.

Mechanical Considerations

In order to conduct an investigation of this type it becomes immediately apparent that a relay must be manufactured for this purpose which will include provisions for varying the heel gap, armature air gap, and the spring tension. This means that some arrangement of the heel piece and armature junction must be devised which will permit the heel gap to easily and accurately be adjusted. In addition, means must be provided for the adjustment and measurement of the armature air gap, residual air gap and spring tension. The modifications to a standard relay for facilitating these adjustments are included in the chapter on methods and procedures.

Electrical Considerations

Measurement of the coil current during the transient period requires some accurate means for recording the current value during this time and relating it to some accurate time base. This requires recording equipment with excellent linearity characteristics and accurate counters. Any variations in the applied step voltages will obviously affect the current in the coil, and therefore a highly stable voltage source is required. The equipment which was used to accomplish the required measurements and provide the voltage source is described in a subsequent chapter.

CHAPTER IV

METHODS AND PROCEDURES

The methods and procedures which were used in obtaining the required experimental data and the subsequent analysis are covered in detail in the subsequent paragraphs. Briefly, this consisted of carrying out the necessary modifications of a standard relay and establishing the necessary instrumentation to permit the accurate recording of the necessary data. In accomplishing this, certain modifications were made to a relay and the data taken was studied and analyzed. After analyzing the data from the first relay which was modified, it was determined that the variation of the heel gap introduced certain angular changes of the armature with respect to the pole face which might detract from the usefulness of the data. Consequently another relay was used that incorporated provisions which permitted the variation of the heel gap to be adjusted without changing the angular relationship of the armature with respect to the pole face. Complete data from both relays is included in this document to permit the reader to compare the results from both relays and become more intimately familiar with the problems.

Test Relays

The first relay used was a Phillips Control Corporation Relay #60A21C with a coil resistance of 500 ohms consisting of 9800 turns of #36 enamel covered wire. This relay was modified to facilitate adjustment of the armature air gap, residual air gap, spring tension and heel gap. The original relay armature spring was replaced with one from an Advance relay. The particular spring adjustment on the Advance relay provided for smooth and accurate adjustment and was one of the best arrangements found on all of the relays which were available. The spring was fastened onto the armature with a stiff wire harness which kept the forces equalized along the axis of the armature hinge pin and thereby reduced the possibility of binding. The harness was attached to the two moment arms, which were at right angles to the armature, by drilling a passageway in each armature moment arm and bending the ends of the stiff wire harness to permit them to be inserted into the two drilled passageways. This allowed the armature to move with minimum transverse forces acting on the spring as the armature motion took place. The holes in the armature hinge were then elongated to permit a sliding adjustment of the heel gap. After the above was accomplished, the relay was ready for test.

The second relay used was similar in general construction as the first relay which was modified, with one important difference. The heel gap of the first relay was varied by changing the relative location of the armature hinge with respect to the heel piece. This caused an angular change of the armature with respect to the magnet pole face. The second relay eliminated this inaccuracy by incorporating means for leaving the armature hinge location stationary while the heel gap was varied by a sliding portion of the heel piece itself. This second relay therefore provided more accurate data for subsequent analysis.

After the experimental results from the first relay were analyzed, it was determined that measurement of the armature motion time would be desirable in that it would facilitate analysis of the experimental data. This information was obtained in the experimental procedure used with the second relay by arranging an insulated contact on the armature which would break a circuit just as the armature starts to move. This set of contacts was used to control the intensity of the oscilloscope cathode ray tube when the armature started to move and thus caused a marker to be displayed on the coil current trace at this point. This marker is the start of the dark part of the oscilloscope trace which is displayed on the photographs of the coil current build-up and as a bright blip on the coil current decay trace. See the simple schematic shown on Fig. 7 for the relay and circuitry arrangement which was used to obtain this information.

Equipment Used for Tests

For the first relay tested the following equipment was used. The oscilloscope used was the Dumont type 332A (dual beam) with a Polaroid Land camera used for photographing the oscilloscope presentations. The time measuring equipment used was the Berkely Universal Counter and Timer Model 550C. A locally manufactured device was used to provide the interconnections, a step voltage for actuating the relay, and to generate pulses for actuating the driven sweep on the oscilloscope. The gram gages which were used for measurement of the relay spring tension were made in France under the trade name CARPO and represented in this

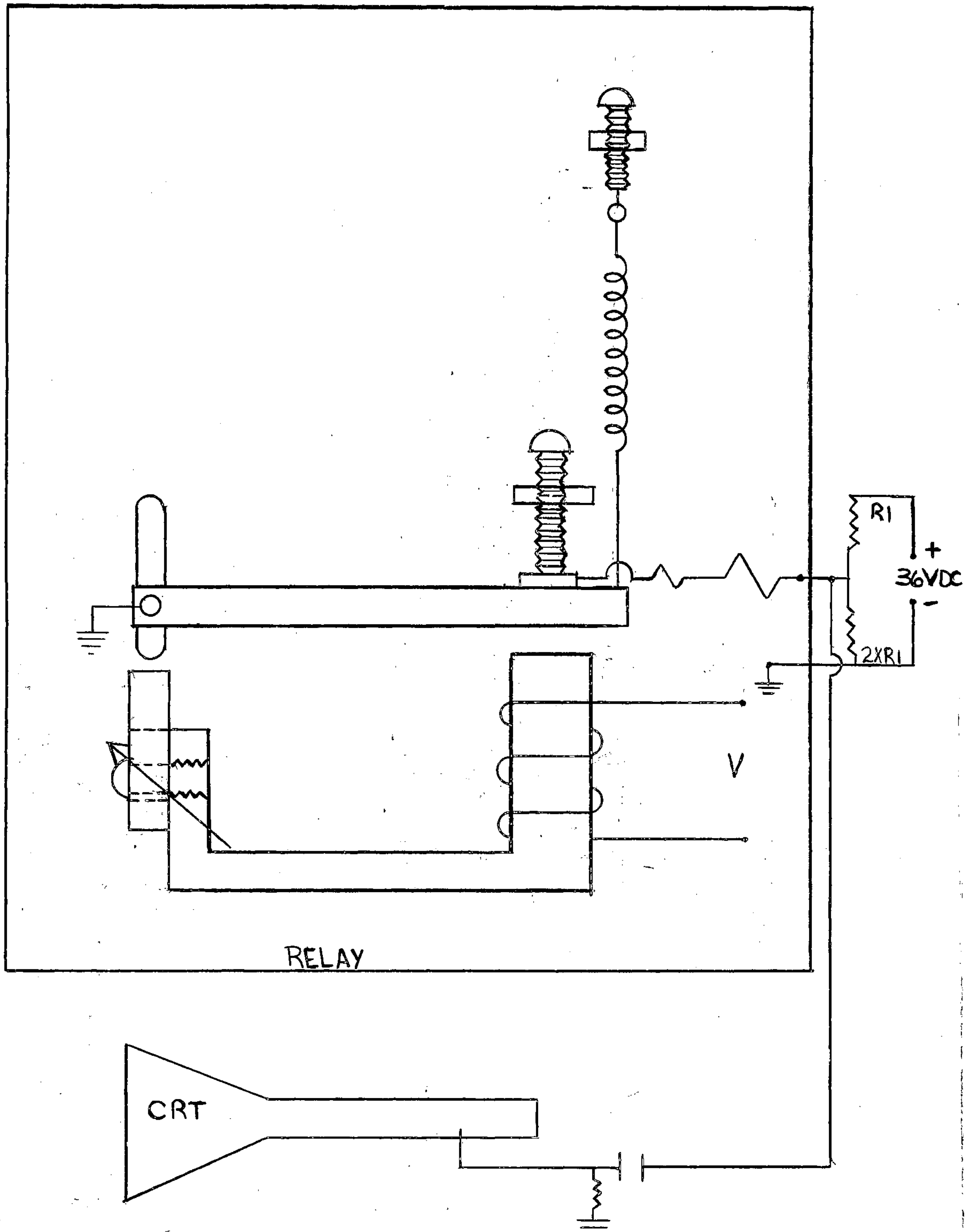


Fig. 7. Simple Diagram of Relay #2, Indicating the Associated Circuitry for Modulating the Intensity of the Cathode Ray Tube Beam

Country by the George Schdrr Company, Inc., of New York City.

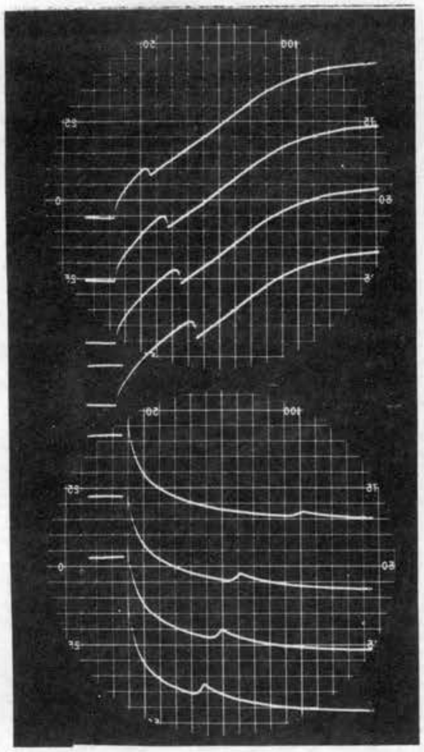
Relay #2 was tested on similar equipment with the exception of the Dumont Oscilloscope and the elimination of the Berkely Counter. A new dual beam Tektronix oscilloscope was used which contained built in calibrated timing circuitry and threrby obviated the necessity of external timing equipment. This equipment became available after the tests on the first relay were completed.

Experimental Results from First Relay (Phillips Control Corporation Relay #60A21C)

The experimental results from the first relay are shown on the succeeding pages of this document. Complete oscillographs for all experimental runs are shown with tabulated data and plotted curves included. This data is subsequently analyzed and conclusions furnished in the final paragraphs of this chapter. By referring to the curves which were obtained by plotting the tabulated data, certain variations which follow definite patterns will be noticed for the lower values of heel gaps. These variations were subsequently determined to be caused by the change in angle of the armature with respect to the magnet pole face as the heel gap was changed from very small values to greater values. At low heel gap settings the armature formed an angle with the heel piece side of the coil pole piece. As the heel gap was increased, this angle became smaller until a point was reached where the armature was parallel with the pole face. At still greater value of heel gap, the armature formed an angle with the front side of the magnet pole face. Although these changes were relatively small, their effect is easily seen on the plotted curves.

Phillips Control Corp. Relay #60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 1

Heel Gap: Minimum
Armature Air Gap: .006"

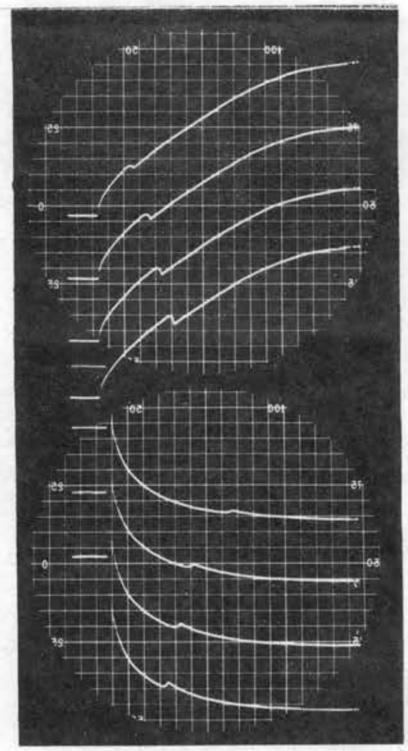
Horiz. Scale: 80ms/4"
Vertical Scale: 46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams



Oscillogram 2

Heel Gap: .010"
Armature Air Gap: .006"

Horiz. Scale: 80ms/4"
Vertical Scale: 46ma/2"

Current Rise

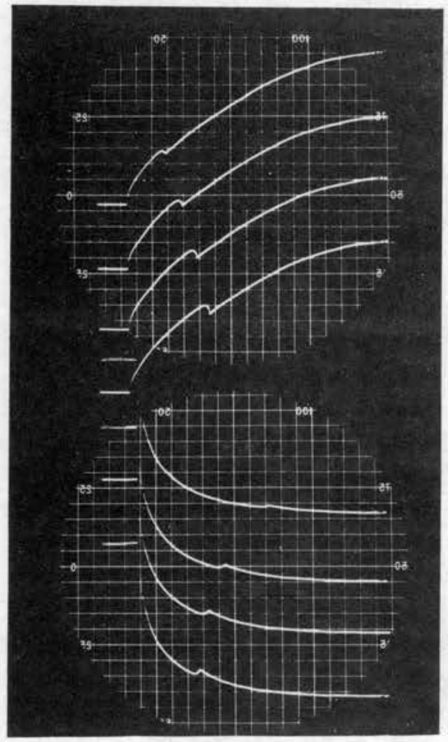
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay #60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 3

Heel Gap	Armature Air Gap
.020"	.006"

Horiz. Scale	Vertical Scale
80ms/4"	46 ma/2"

Current Rise

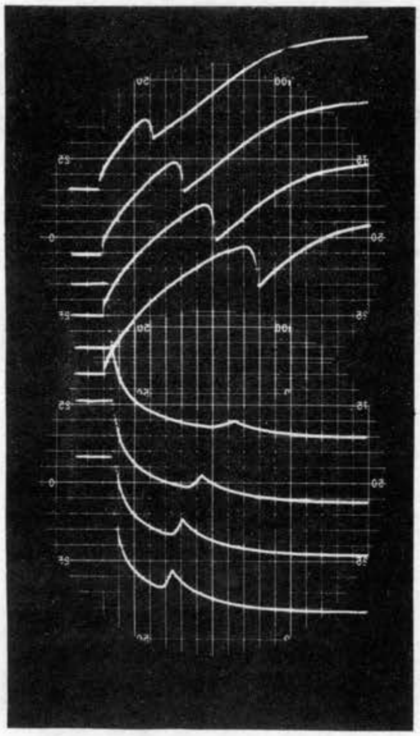
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay #60A21C

Coil Res. 500 ohms, 9800-36EC. Steady State Current 46 MA



Oscillogram 4

Heel Gap	Armature Air Gap
Minimum	.012"

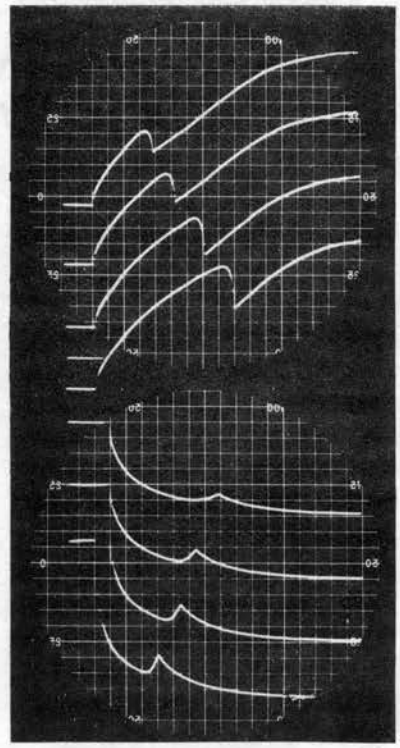
Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams



Oscillogram 5

Heel Gap	Armature Air Gap
.002"	.012"

Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

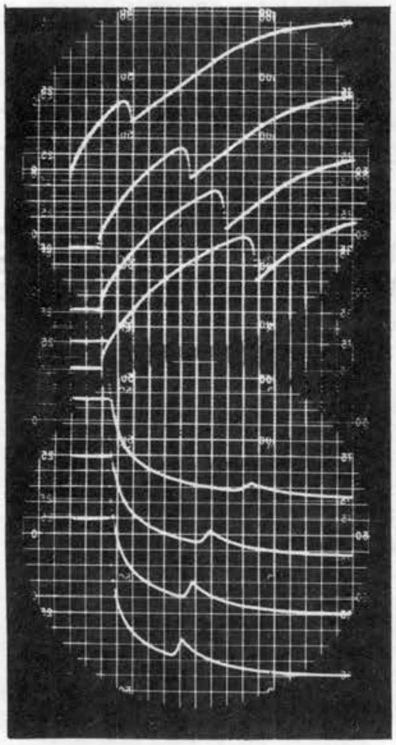
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

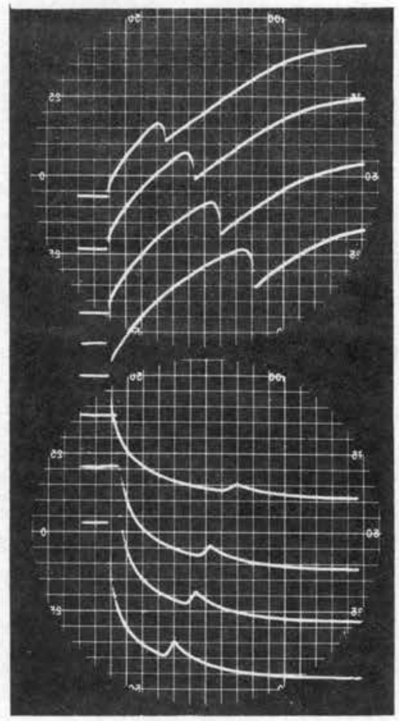
Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay # 60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 6



Oscillogram 7

Heel Gap .004" — Armature Air Gap .012"

Horiz. Scale 80ms/4" — Vertical Scale 46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Heel Gap .006" — Armature Air Gap .012"

Horiz. Scale 80ma/4" — Vertical Scale 46ma/2"

Current Rise

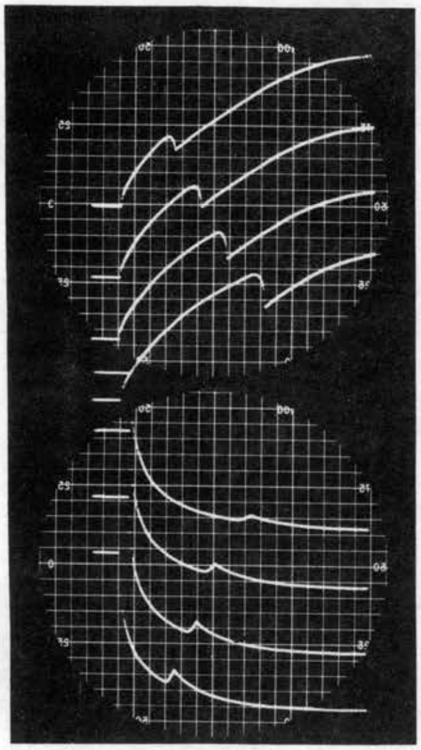
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay # 60A21C

Coil Res. 500 ohms, 9800-46EC, Steady State Current 46 MA



Oscillogram 8

Heel Gap	Armature Air Gap
.008"	.012"

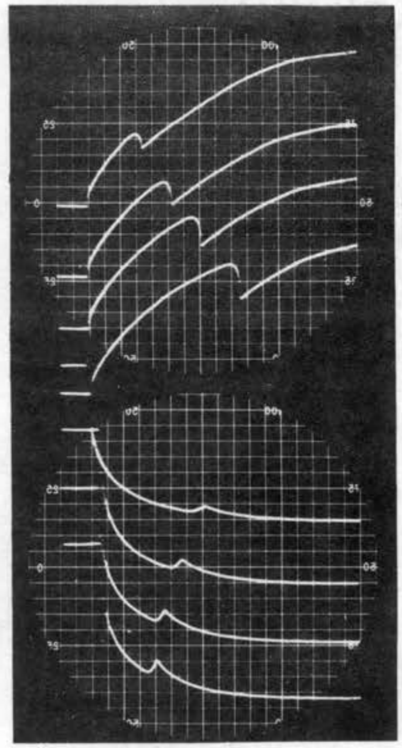
Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams



Oscillogram 9

Heel Gap	Armature Air Gap
.010"	.012"

Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

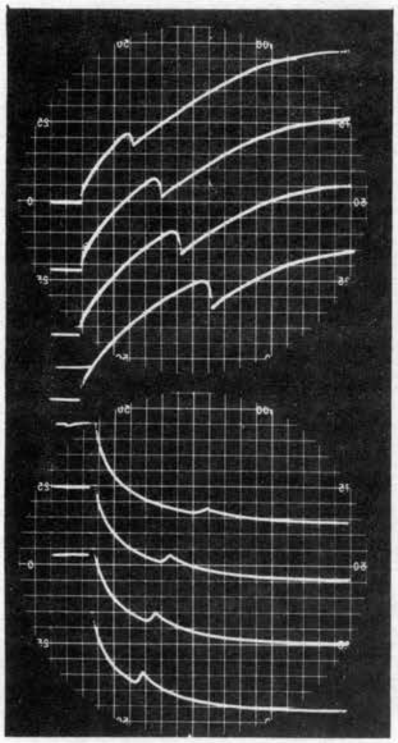
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay #60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 10

Heel Gap .012"   Armature Air Gap .012"

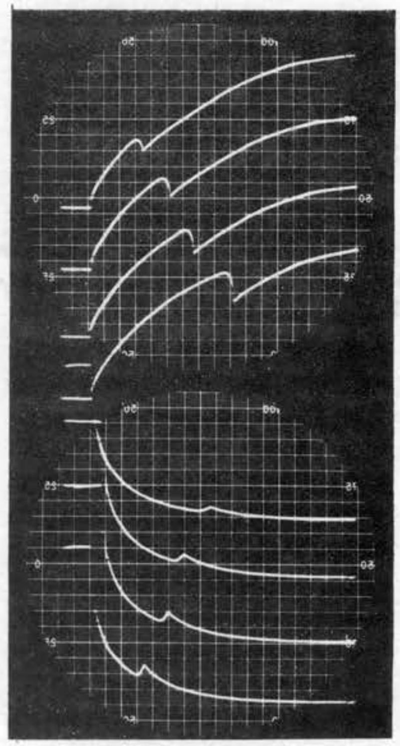
Horiz. Scale 80ms/4"   Vertical Scale 46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams



Oscillogram 11

Heel Gap .020"   Armature Air Gap .012"

Horiz. Scale 80ms/4"   Vertical Scale 46ma/2"

Current Rise

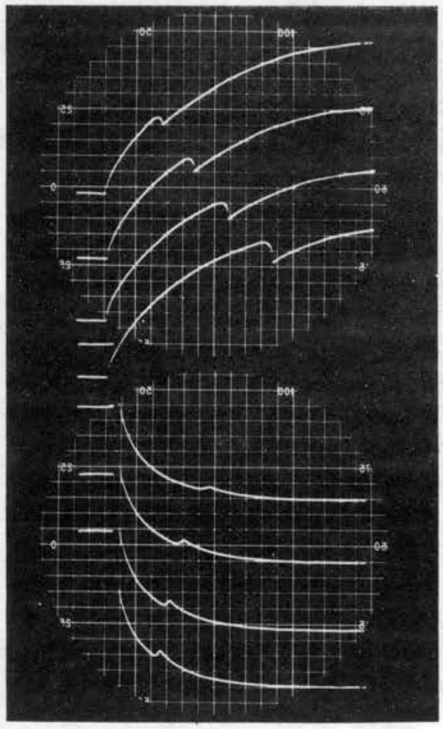
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay #60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 12

Heel Gap	Armature Air Gap
.040"	.012"

Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

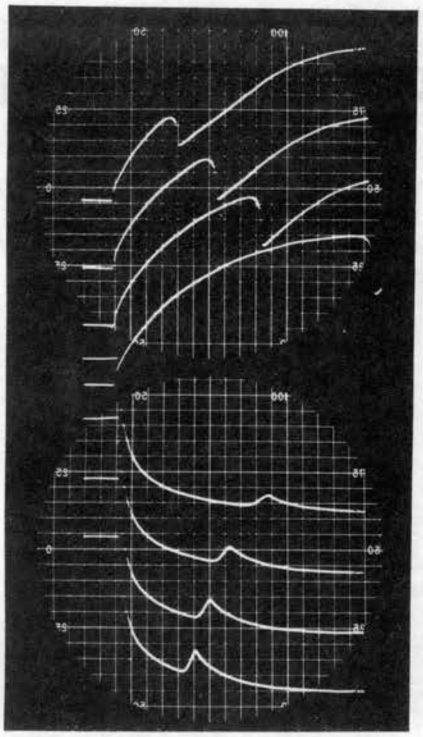
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay # 60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 13

Heel Gap	Armature Air Gap
Minimum	.018"

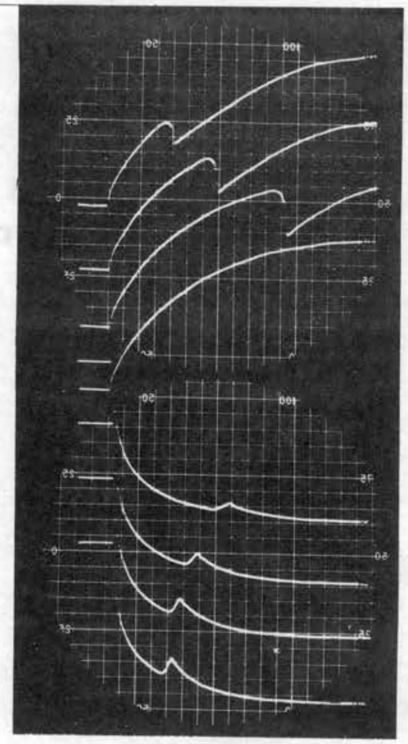
Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams



Oscillogram 14

Heel Gap	Armature Air Gap
.010"	.018"

Horiz. Scale	Vertical Scale
80ms/4"	46ma/2"

Current Rise

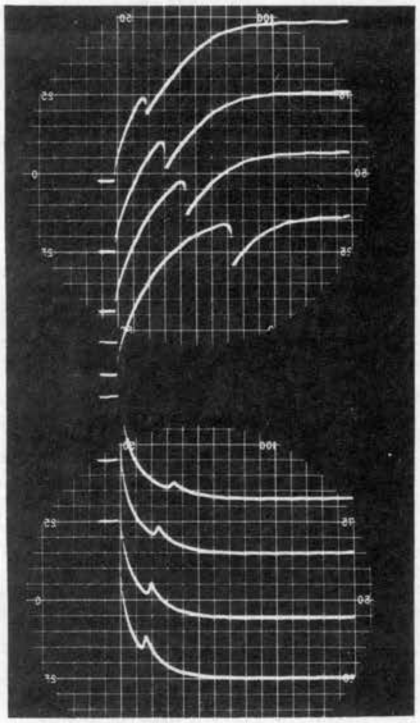
Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Phillips Control Corp. Relay #60A21C

Coil Res. 500 ohms, 9800-36EC, Steady State Current 46 MA



Oscillogram 15

Heel Gap	Armature Air Gap
.020	.018"

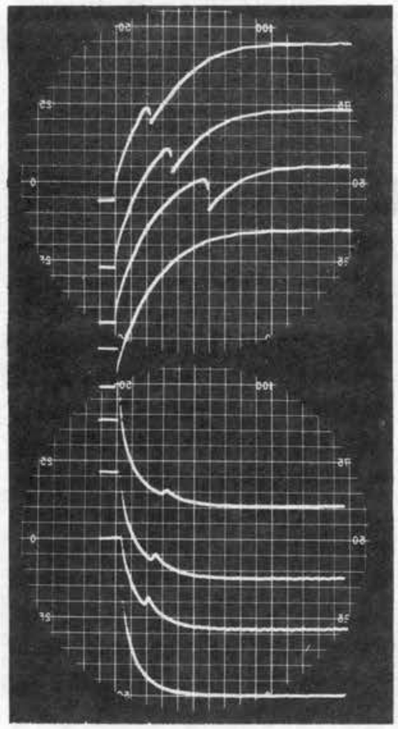
Horiz. Scale	Vertical Scale
160ms/4"	46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams



Oscillogram 16

Heel Gap	Armature Air Gap
.040"	.018"

Horiz. Scale	Vertical Scale
160ms/4"	46ma/2"

Current Rise

Osc. #	Spring Tension
1	75 grams
2	150 grams
3	225 grams
4	300 grams

Current Decay

Osc. #	Spring Tension
5	75 grams
6	150 grams
7	225 grams
8	300 grams

Tabulated Data

Heel Gap - Minimum — Armature Air Gap - .006"

Spring Tension (grams)	Operate Time (ms)	Release Time (ms)	i_m (MA)	I_{ss} (MA)
75	10	42	11.5	46
150	14	27	13.8	46
225	17	22	17.5	46
300	20	17	19.3	46

Heel Gap - .010" — Armature Air Gap - .006"

Spring Tension (grams)	Operate Time (ms)	Release Time (ms)	i_m (MA)	I_{ss} (MA)
75	9	29	13.8	46
150	13	21	17.5	46
225	16	18	19.8	46
300	19	15	23.0	46

Heel Gap - .020" — Armature Air Gap - .006"

Spring Tension (grams)	Operate Time (ms)	Release Time (ms)	i_m (MA)	I_{ss} (MA)
75	11	33	15.64	46
150	14.5	21	18.4	46
225	18	16	21.2	46
300	21	14	27.6	46

Tabulated Data

Spring Tension (grams)	Operate Time (ms)	Release Time (ms)	i_m (MA)	I_{ss} (MA)
Heel Gap - Minimum		Armature Air Gap - .012"		
75	13.6	25.2	15.2	46
150	21.2	18.8	18.4	46
225	29.2	15.2	22.5	46
300	40	12	27.6	46
Heel Gap - .002"		Armature Air Gap - .012"		
75	15.6	21.6	16.1	46
150	20.8	18.4	18.4	46
225	28	15.2	21.2	46
300	36	12.8	24.4	46
Heel Gap - .006"		Armature Air Gap - .012"		
75	15.2	28	15.6	46
150	21.6	21.2	21.2	46
225	28.8	16.8	23	46
300	36.8	14	27.6	46
Heel Gap - .008"		Armature Air Gap - .012"		
75	14	26.4	16.1	46
150	20.4	18.8	21.2	46
225	27.6	14.8	23	46
300	46.8	12	30.36	46

Tabulated Data

Spring Tension (grams)	Operate Time (ms)	Release Time (ms)	i_m (MA)	I_{ss} (MA)
Heel Gap - .010"		Armature Air Gap - .012"		
75	13.6	24	16.6	46
150	20.8	18	18.9	46
225	28	14	23.9	46
300	39.2	12	27.6	46
Heel Gap - .012"		Armature Air Gap - .012"		
75	12.4	24.8	16.6	46
150	20	18	21.2	46
225	25.6	14	23.5	46
300	33.2	12.4	28.5	46
Heel Gap - .020"		Armature Air Gap - .012"		
75	14	27.6	17	46
150	20	18.8	21.2	46
225	27.2	13.8	25.8	46
300	36.8	12	29.9	46
Heel Gap - .040"		Armature Air Gap - .012"		
75	14.8	21.2	20.2	46
150	22.4	16	25.8	46
225	32	12	29.9	46
300	43.2	11	37.3	46

Tabulated Data

Spring Tension (grams)	Operate Time (ms)	Release Time (ms)	i_m (MA)	I_{ss} (MA)
Heel Gap - Minimum		**Armature Air Gap - .018"**		
75	17	32	16.5	46
150	30.4	29	20.2	46
225	38	21	24.4	46
300	68	16.8	27.8	46
Heel Gap - .010"		**Armature Air Gap - .018"**		
75	17	24.8	18.4	46
150	28	21.2	23.5	46
225	46	14.4	27.6	46
300	--	12	--	46
Heel Gap - .020"		**Armature Air Gap - .018"**		
75	16	24	19.3	46
150	25.6	17.6	24.4	46
225	37.6	16.8	29	46
300	60	10.4	32.5	46
Heel Gap - .040"		**Armature Air Gap - .018"**		
75	18	23.2	22.1	46
150	29.6	17.6	27.1	46
225	48	13.6	32.7	46

300 --- Armature failed to close for this spring tension

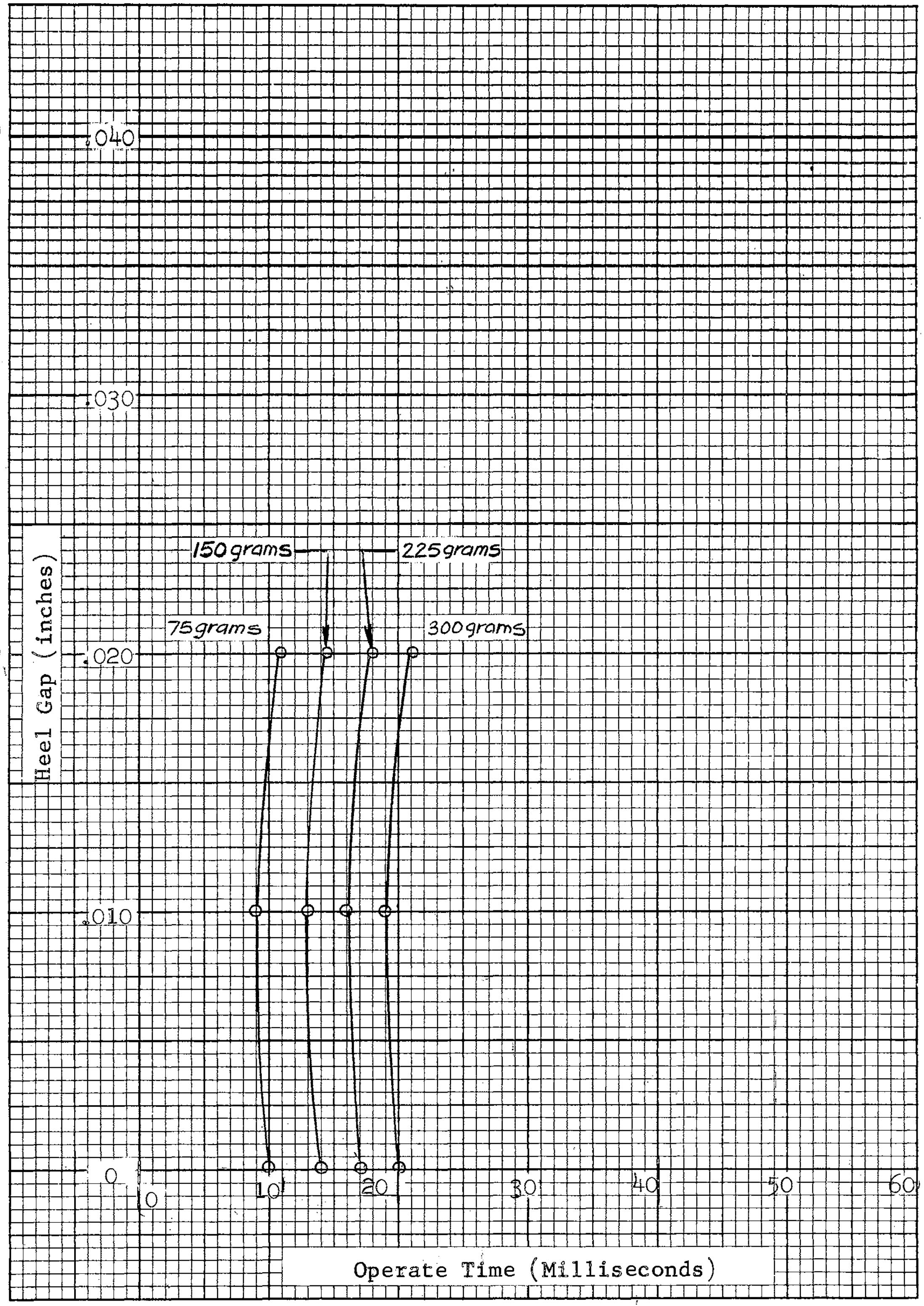


Fig. 8. Heel Gap vs Operate Time for Various Spring Tensions and with Armature Air Gap Constant at .006"

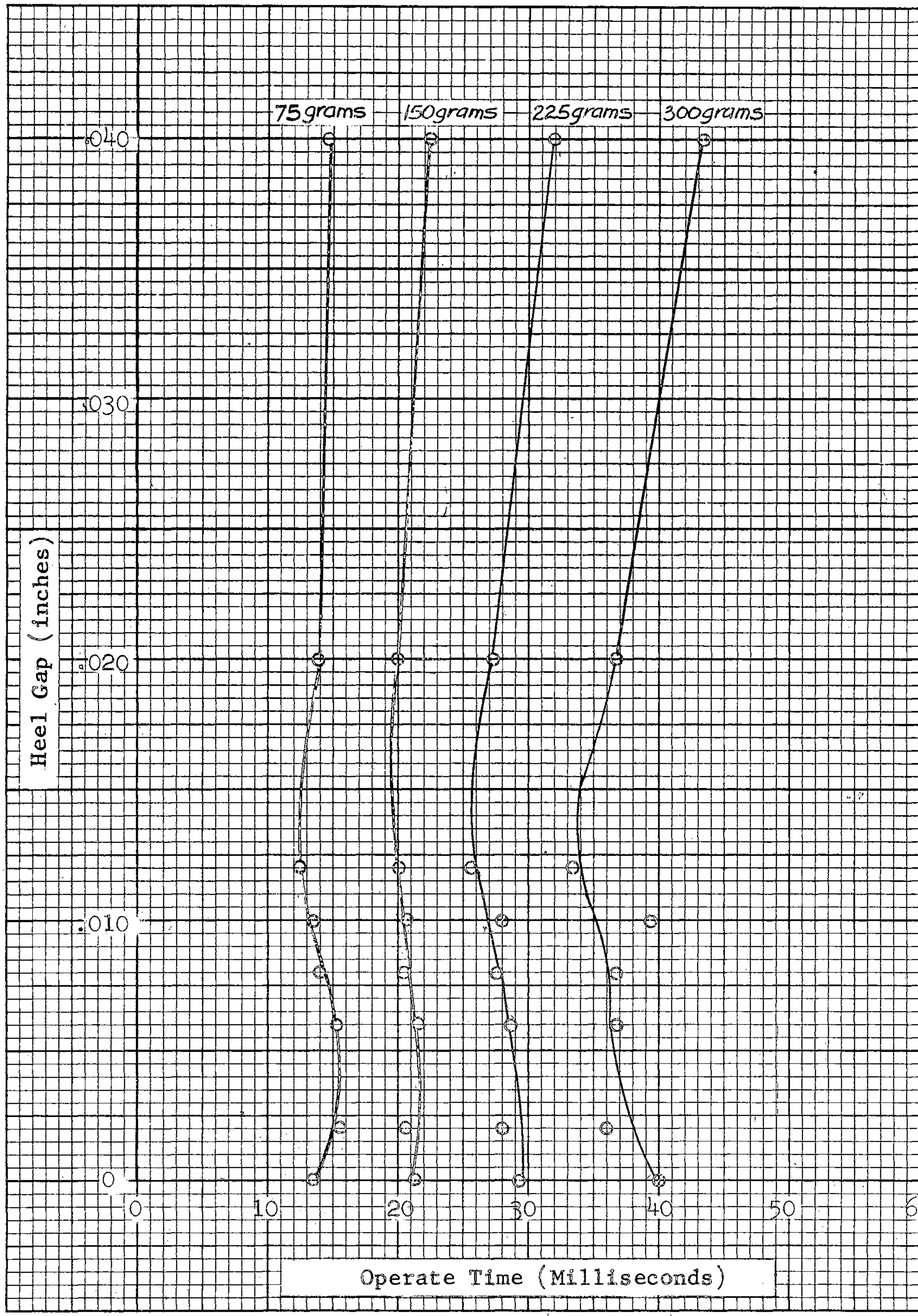


Fig. 9. Heel Gap vs Operate Time for Various Spring Tensions and with Armature Air Gap Constant at .012"

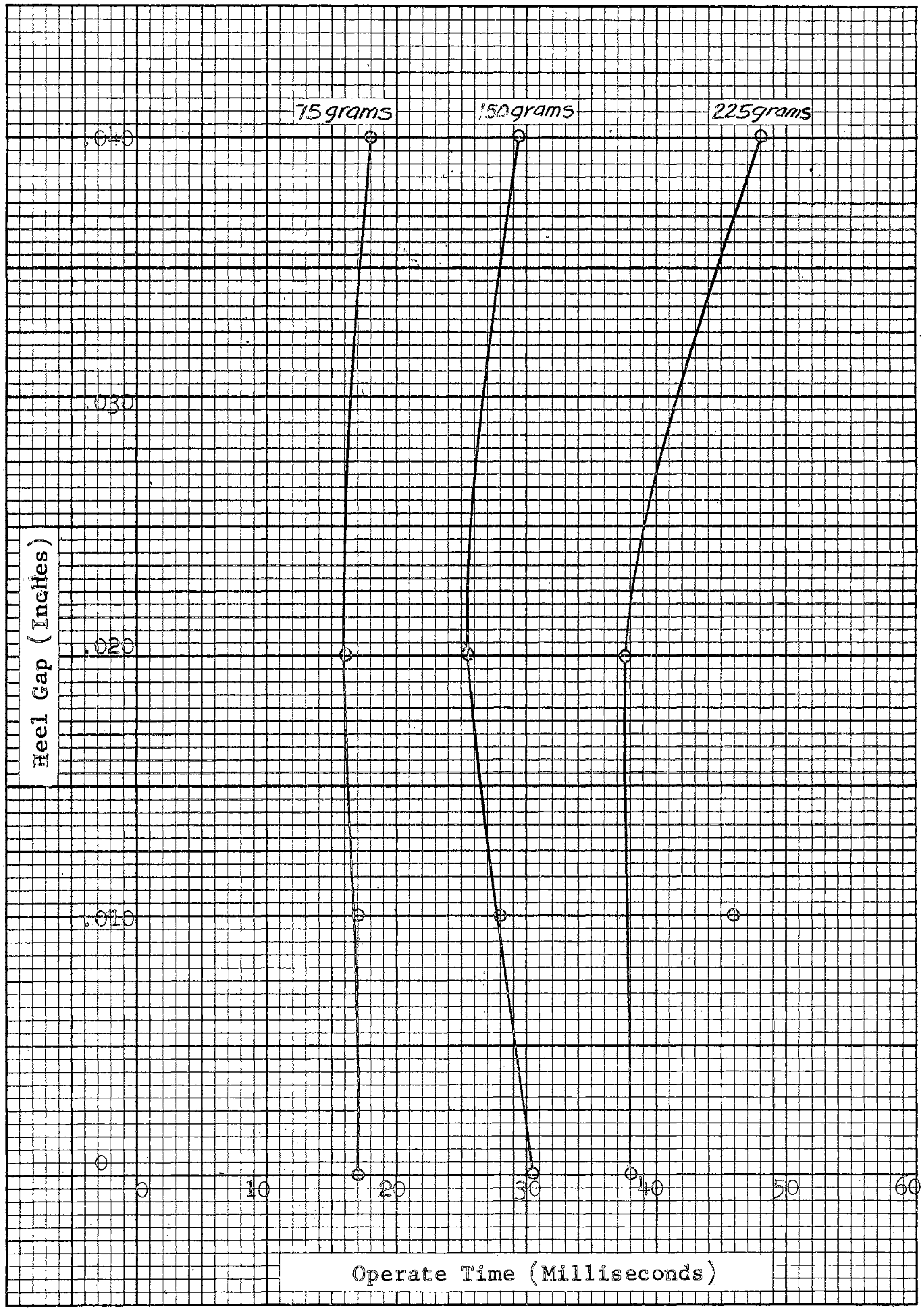


Fig. 10. Heel Gap vs Operate Time for Various Spring Tensions with Constant Armature Air Gap of .018"

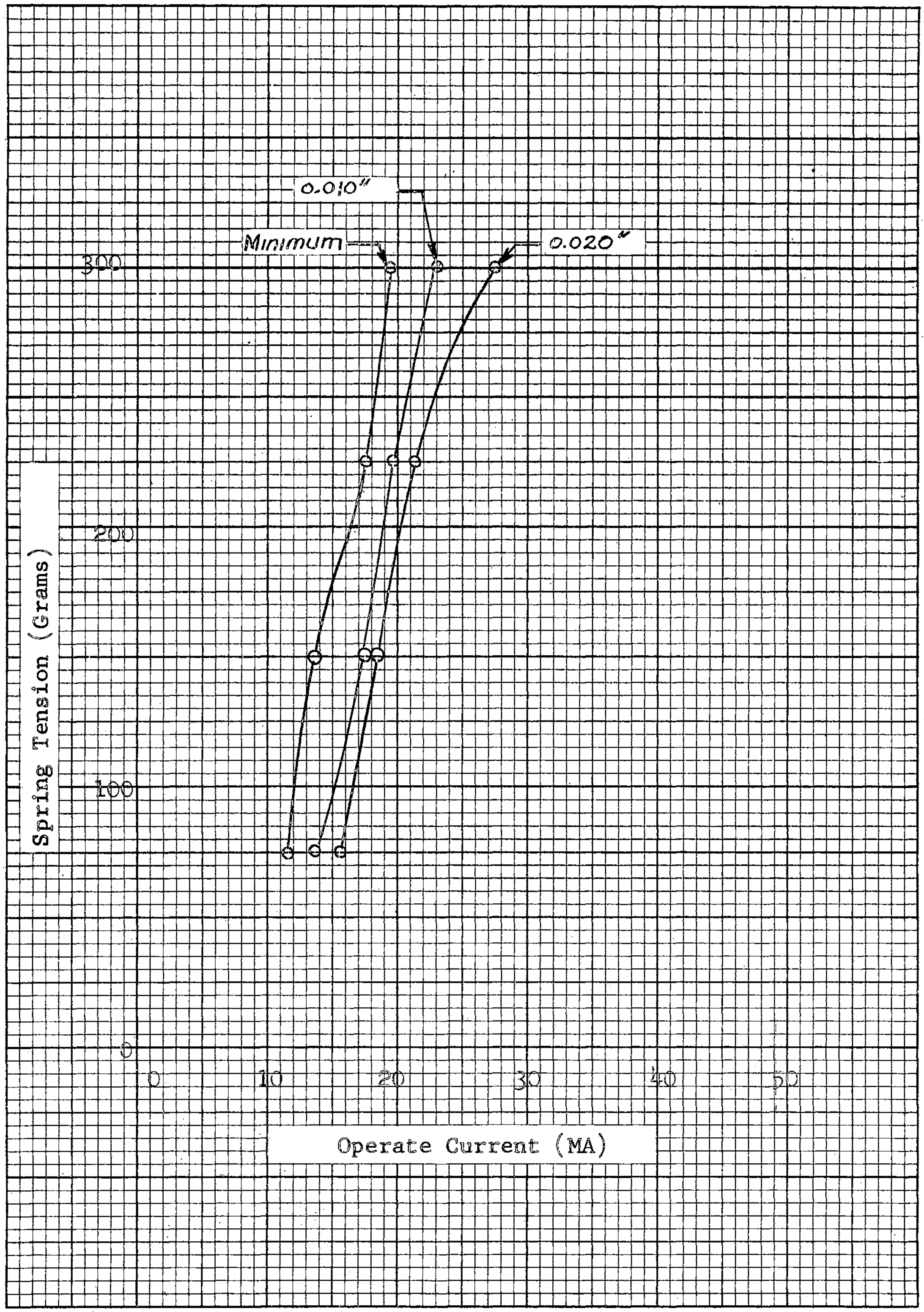


Fig. 11. Operate Current vs Spring Tension at Various Heel Gaps with Armature Air Gap Constant at .006"

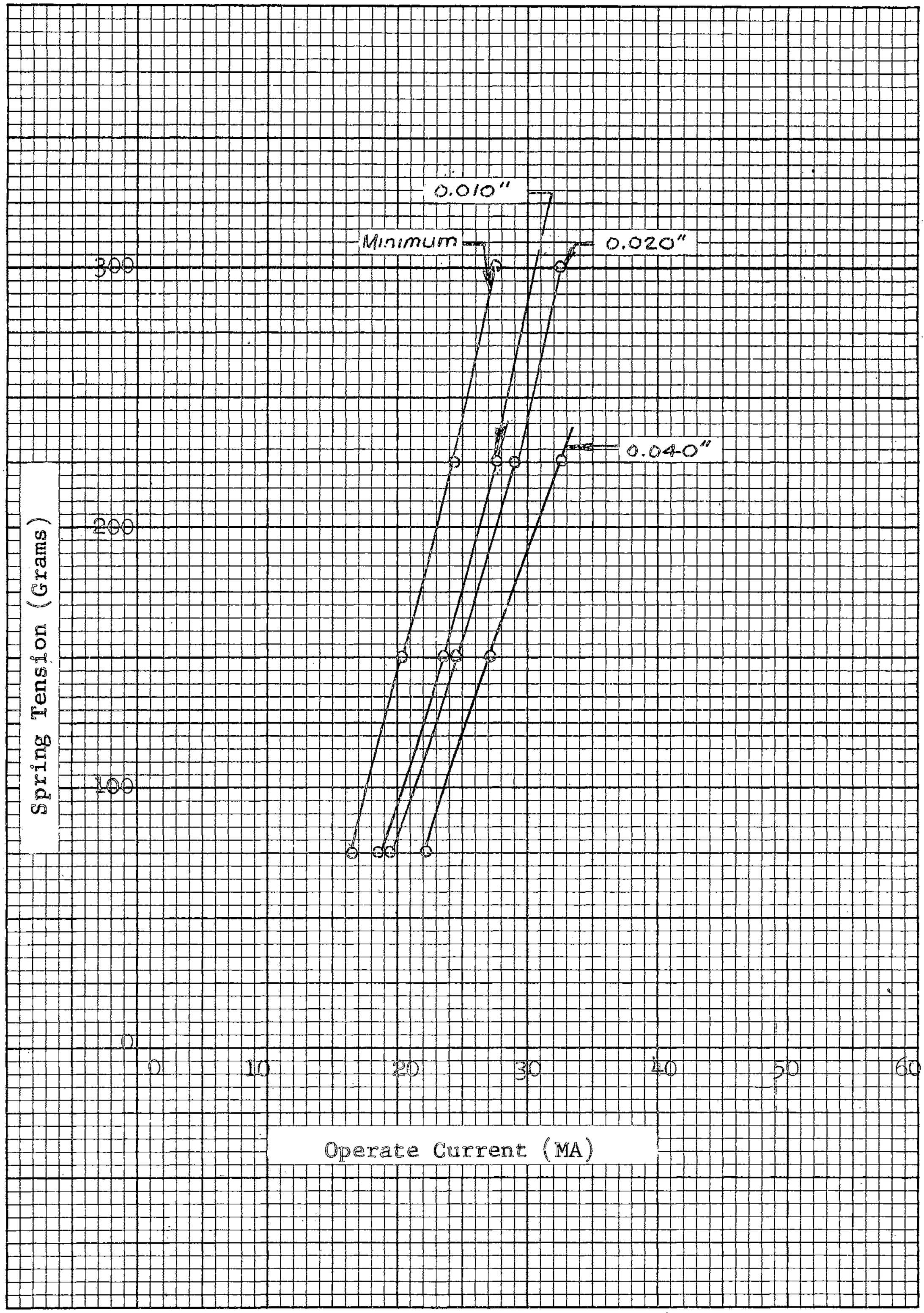


Fig. 12. Operate Current vs Spring Tension for Various Heel Gaps with Armature Air Gap Constant at .018"

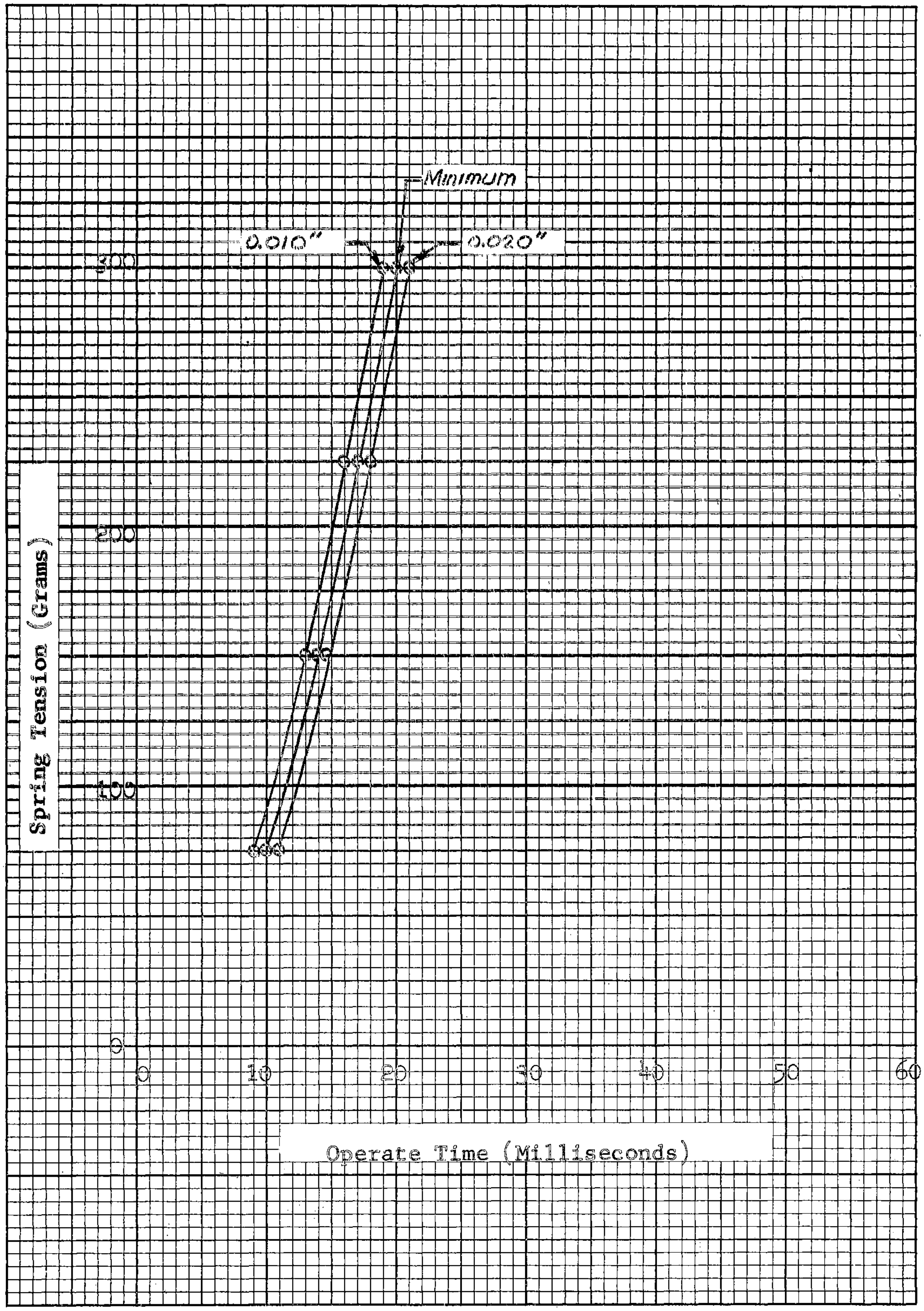


Fig. 13. Operate Time vs Spring Tension for Various Heel Gaps with Armature Air Gap Constant at .006"

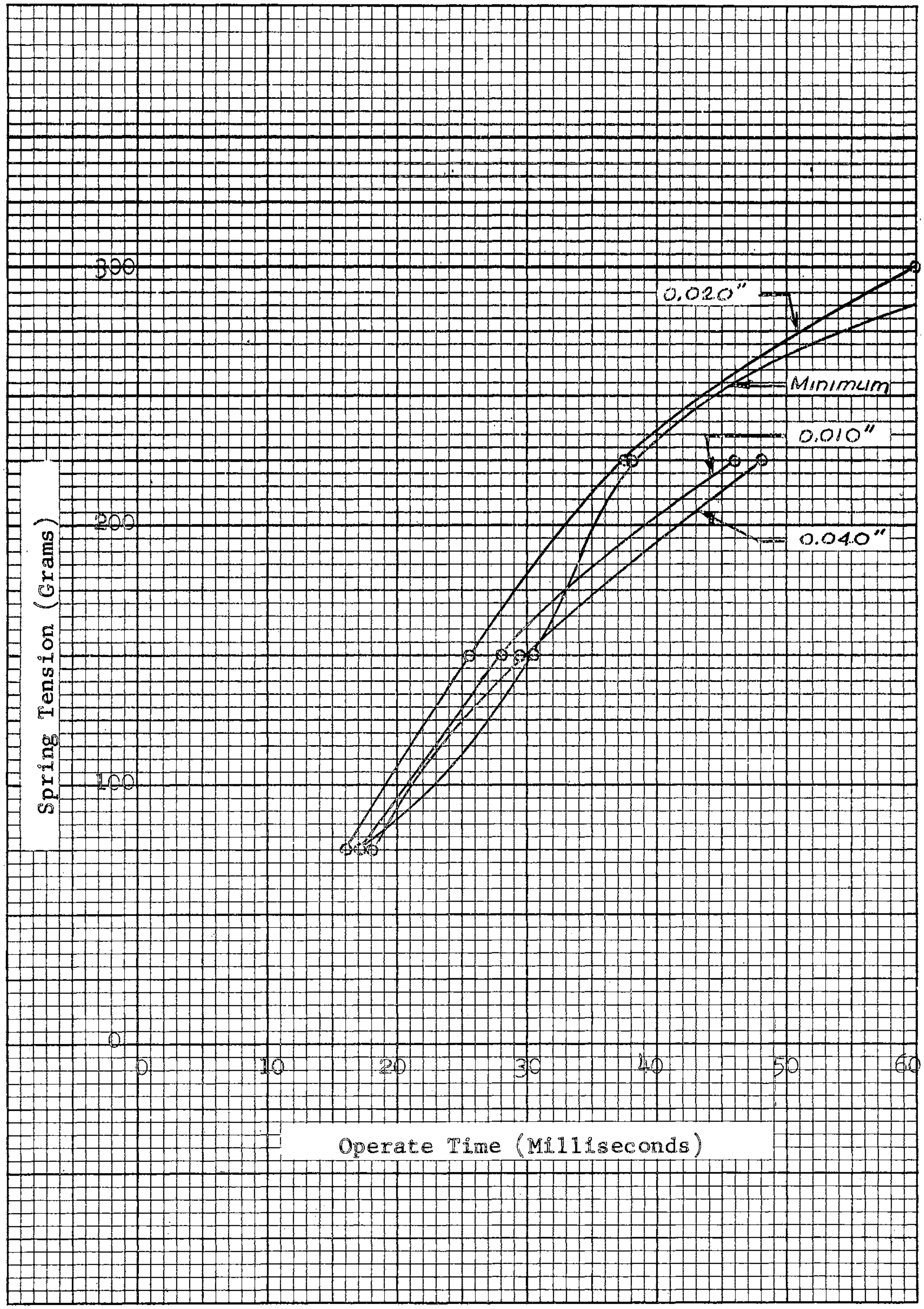


Fig. 14. Operate Time vs. Spring Tension with Various Heel Gap Settings and Armature Air Gap Constant at .018"

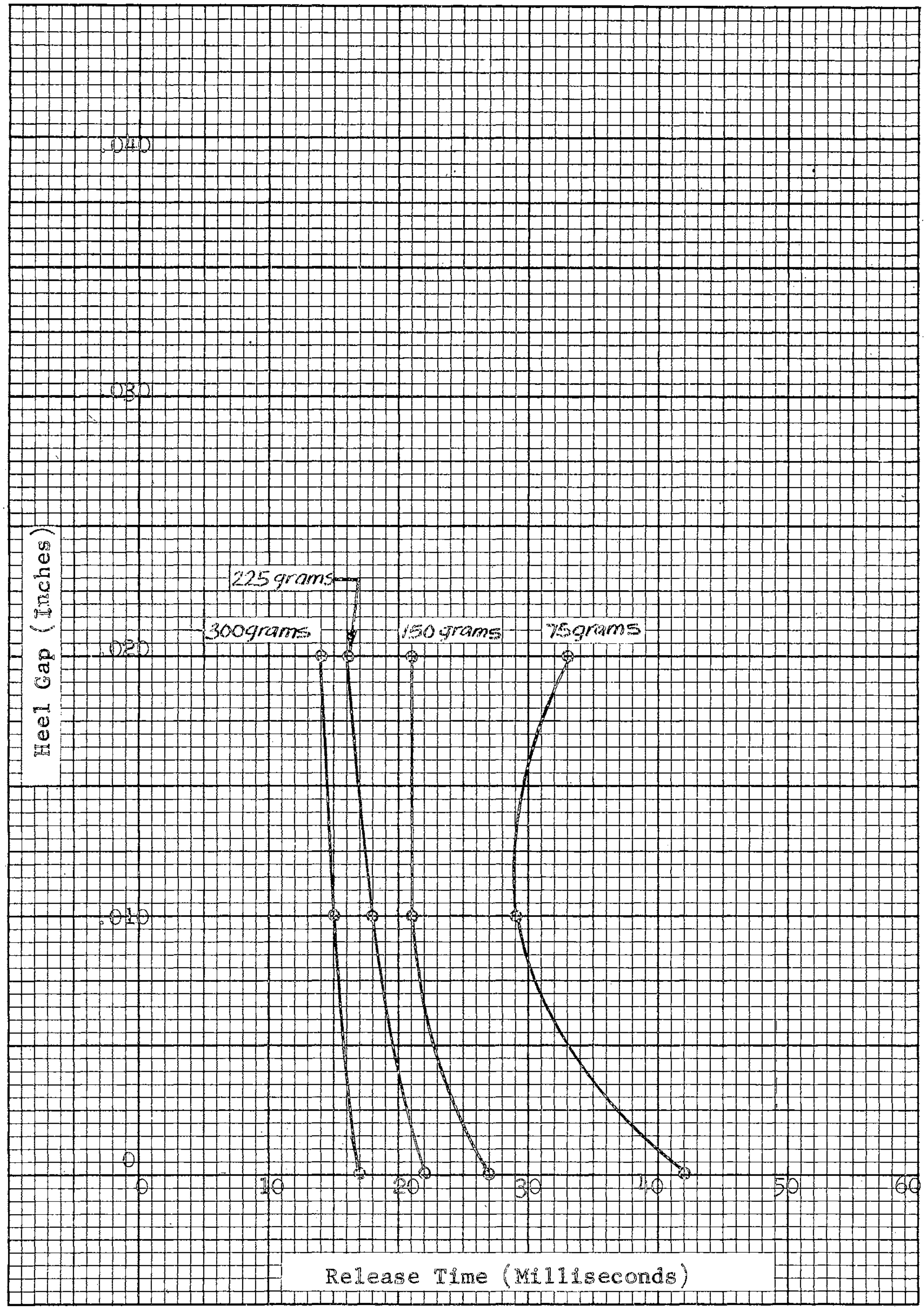


Fig. 15. Release Time vs Heel Gap for Various Spring Tensions and Armature Air Gap Constant at .006"

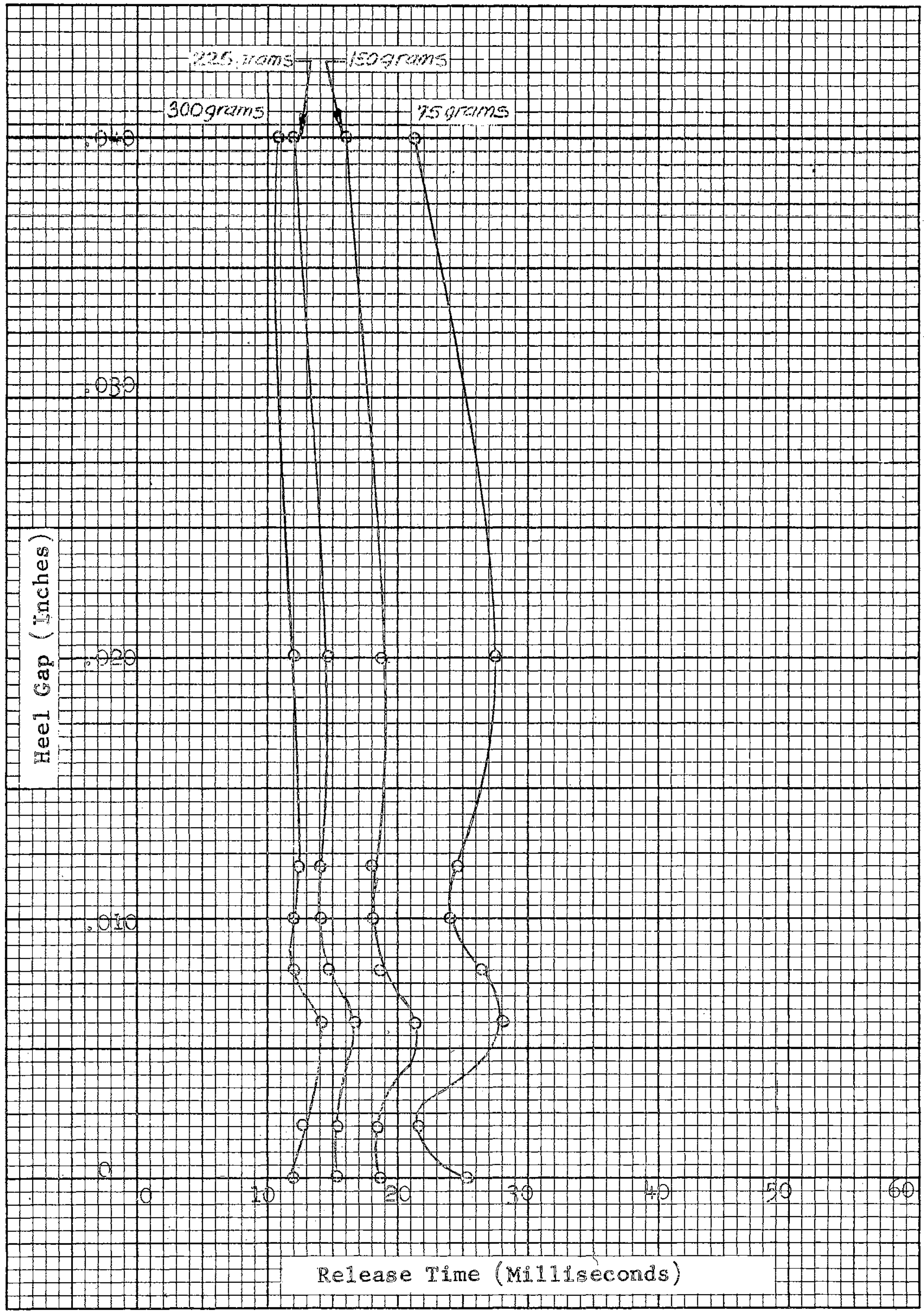


Fig. 16. Release Time vs Heel Gap for Various Spring Tensions and with Armature Air Gap Constant at .012"

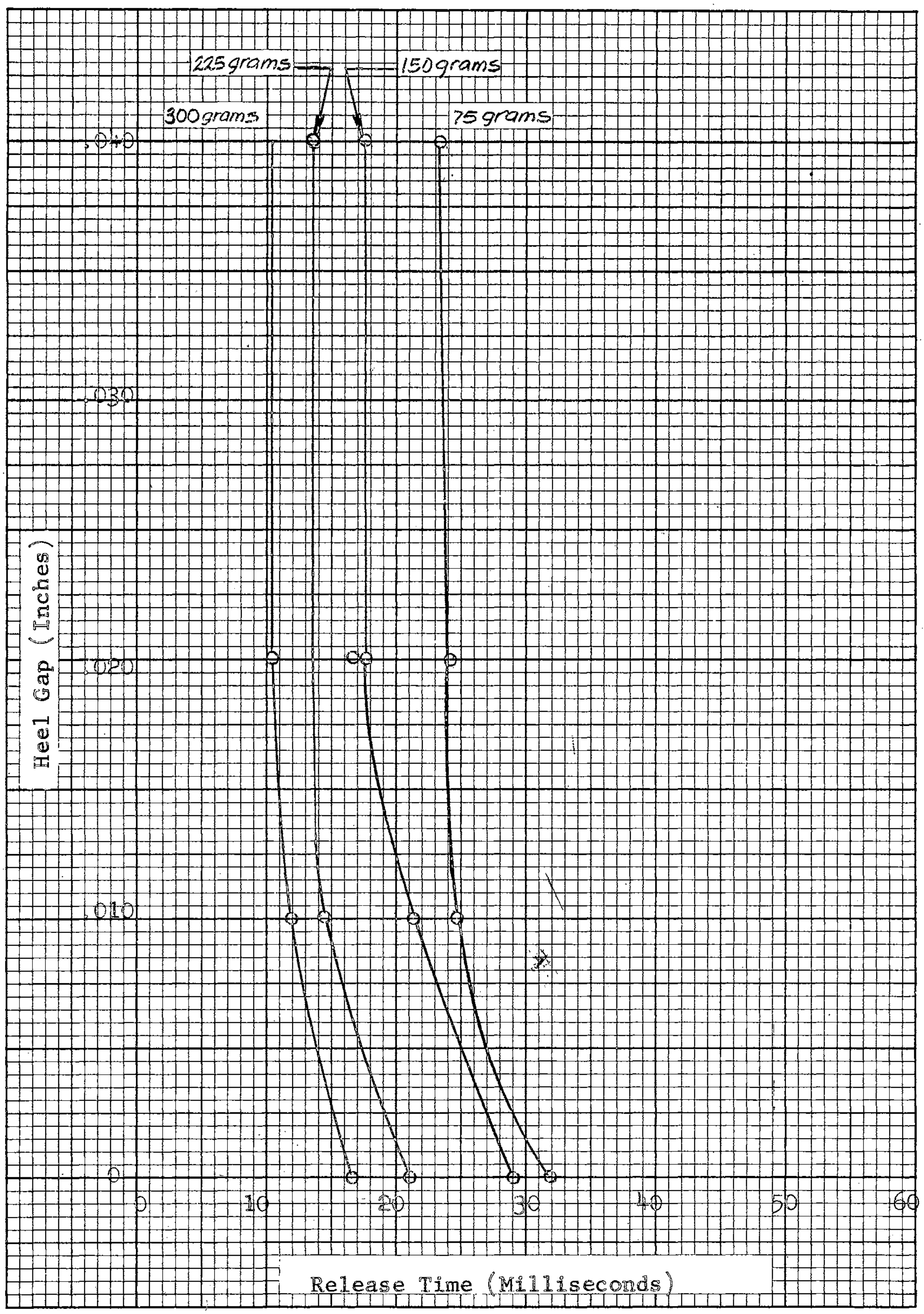


Fig. 17. Release Time vs Heel Gap for Various Spring Tensions and with Armature Air Gap Constant at .018"

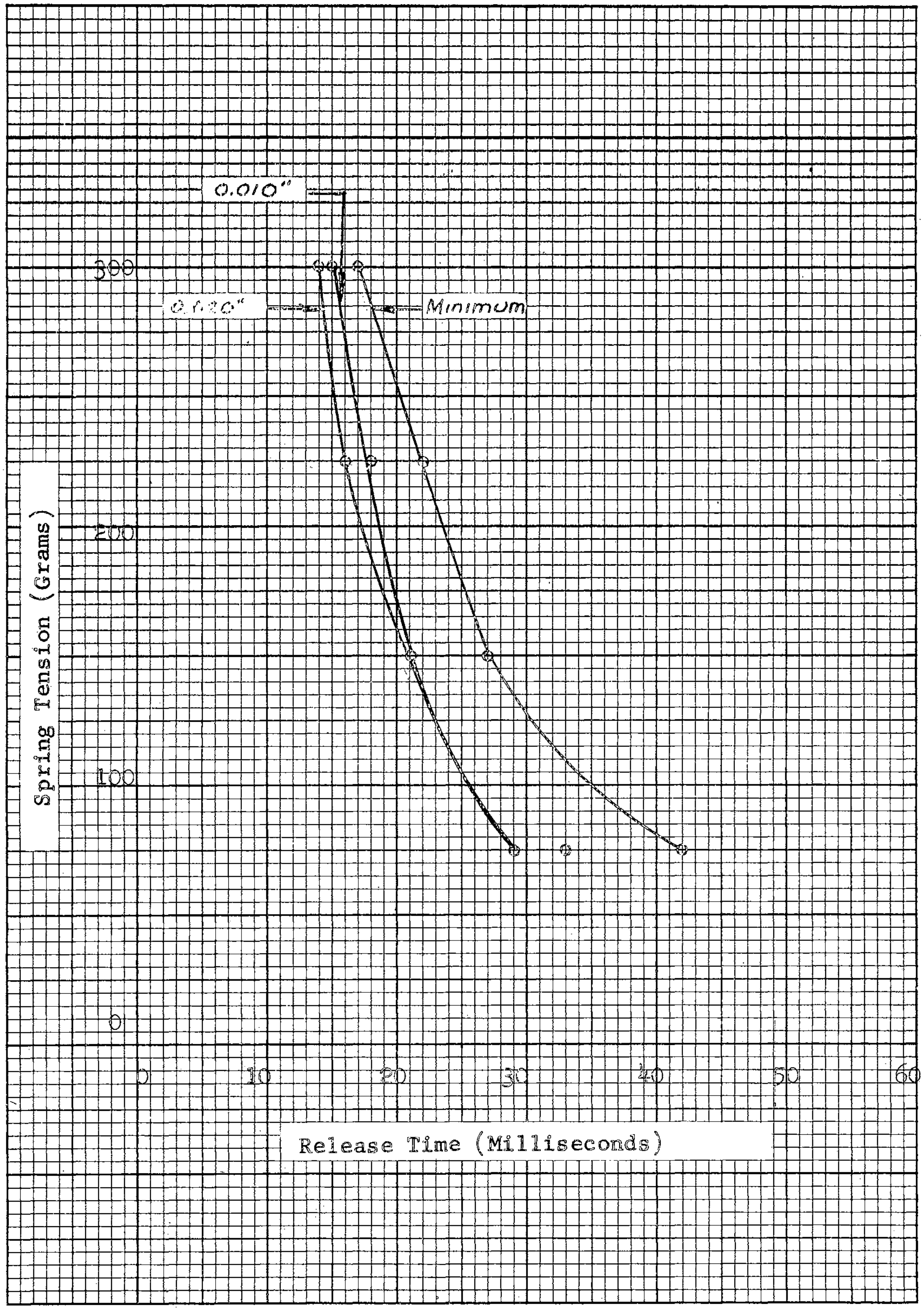


Fig. 18. Release Time vs Spring Tension for Various Values of Heel Gap and with Armature Air Gap Constant at .006"

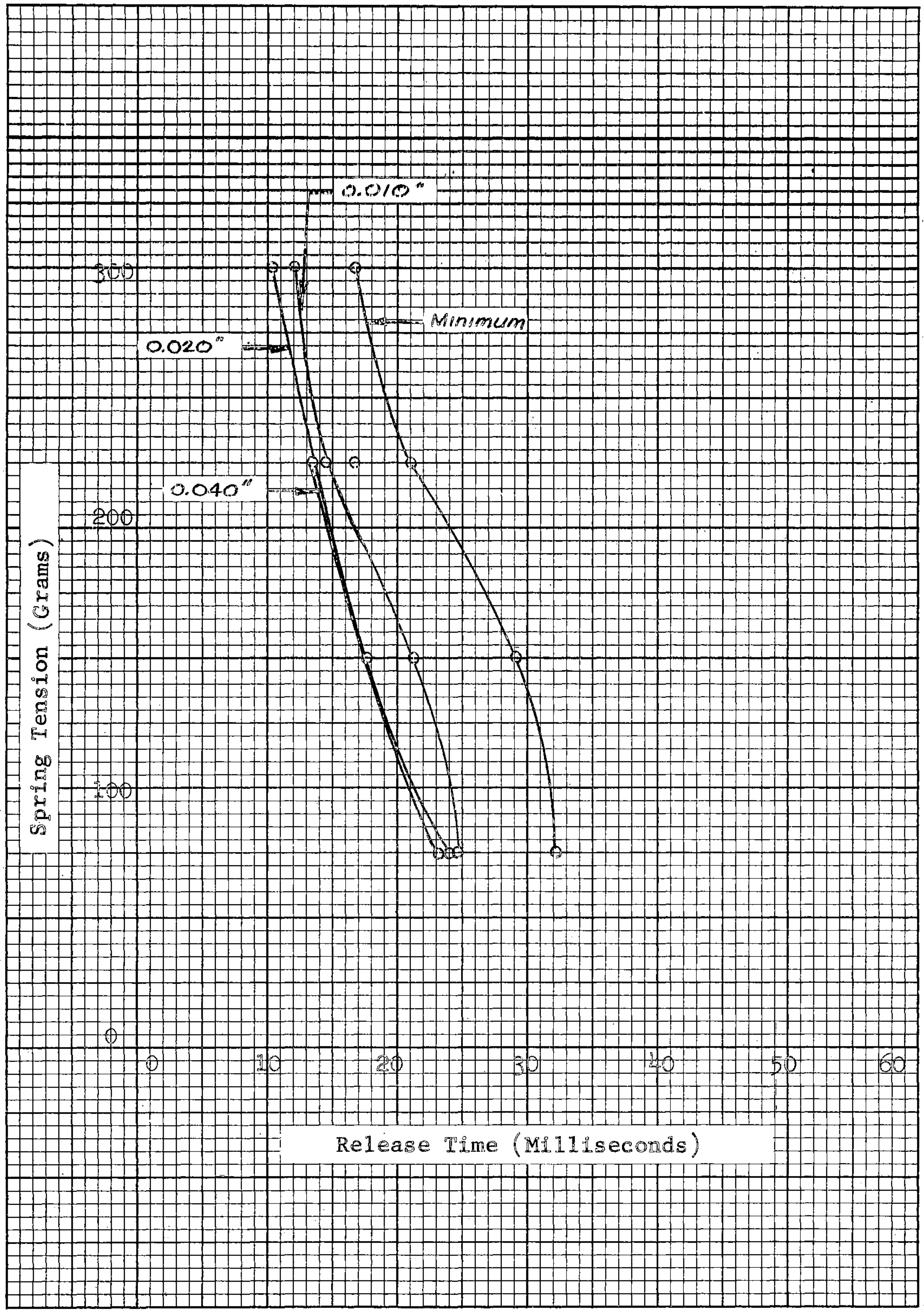


Fig. 19. Release Time vs Spring Tension for Selected Heel Gap Settings

CHAPTER V

ANALYSIS OF RESULTS FROM EXPERIMENTAL DATA, RELAY #1

In studying the experimental data from relay #1 which is included in the preceding chapter, it becomes immediately apparent that the results indicate certain patterns which seem significant. In an attempt to explain the significant information, the findings were broken down into separate areas for analysis. Although these areas are considered separately for purposes of simplification of the analysis, they are not independent and overall evaluation must be undertaken with this in mind. For example -- when studying the operate current vs heel gap settings, the relationships might be linear but when considering the operate current and time relationships it is found that the current does not vary linearly with time. It becomes obvious therefore, that evaluation must consider both areas even though they are discussed separately.

Operate Time vs Heel Gap

The information which is shown and plotted as curves on Figures 8, 9 and 10 in the preceding chapter indicates that the operate time varied as the heel gap changed. Starting with minimum heel gap and the corresponding operate time for this setting, as the heel gap is increased the operate time is increased up to a certain value of heel gap. As the heel gap is increased still further, the operate time decreases for a time and then increases again. In attempting to analyze the reasons for this change in the operating time of the relay, two hypotheses were developed. The first was that the operate time decreased for certain heel gap settings because the rate of increase of energy in the magnetic field might be greater during the armature motion and the second was that the relay used for the laboratory experimental work might be introducing an error in that there was a very slight change in the angle of the armature with respect to the magnetic pole face as the heel gap was varied. In order to test the first hypothesis, it was determined that additional experimental runs must be made with relay #2 which was modified to permit markers to be displayed on the oscillographs to indicate armature motion time. The second hypothesis was tested by also using relay #2 in a new set of experimental runs. Since relay #2 permitted adjustment of the heel gap without the angle between the armature and pole face changing, similar data on this relay would eliminate the validity of the second hypothesis. See Fig. 20a, 20b and 20c for an illustration of the angular changes between the armature and pole face as the heel gap is varied.

Examination of the operate time for constant spring tensions vs heel gap settings which are plotted on curves shown in Fig. 9 indicates that there is an optimum heel gap setting for shortest operate time of the relay. Since as pointed out in the preceeding paragraph the point in time where the armature starts to move must increase with increased heel gap setting, then it becomes apparent that the armature motion time must decrease rapidly at this heel gap setting in order for the overall operate time to decrease. The hypothesis for this occurence will be discussed in the analysis of the results from the relay #2. All of the experimental results indicated that the point of most rapid operation

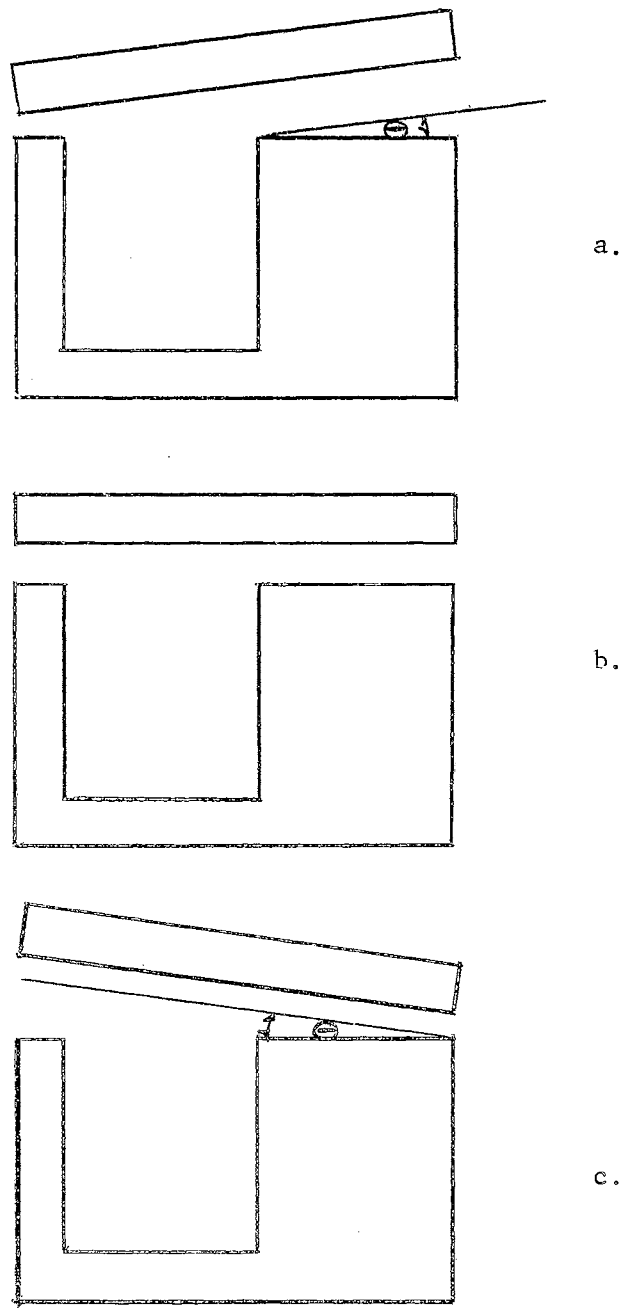


Fig. 20. Variation of Angle Between Armature and Pole Face as Heel Gap is Varied

occured near heel gap settings which approached the armature air gap setting. This could not be correlated with any other available information and may be merely coincidental. In order to confirm that armature motion time is shortest for a particular heel gap setting, it was decided that experimental data on armature motion time would be necessary. Relay #2 was modified to include provisions for modulating the oscilloscope as the armature motion started and again when the motion ceased. The results of the experimental data and the analysis of the operation of relay #2 will be discussed in a subsequent chapter.

Operate Current vs Spring Tension

Figures 11 and 12 contain the curves for the operate current vs spring tension. The operate current is the value of current which exists at the moment that the armature completes its motion. The curve sheet on Fig. 11 is plotted for a constant armature air gap of .006" and the curves on Fig. 12 show the corresponding information for operate current vs spring tension at various heel gap positions with the armature air gap held constant at .018".

The curves shown on Fig. 12 are considered to be more accurate because small errors in adjustment of the larger armature air gap setting during experimental runs do not affect the results as much as for the smaller air gap setting. For this reason only the curves on Fig. 12 will be used in the analysis

Careful examination of this set of curves reveals that the increase in operate current with spring tension is linear and as the heel gap is increased, the slope of the line decreases. If constant μ is assumed, then the current where the armature just starts to move will increase linearly with increase in spring tension. Since the slope of the line indicating operate current decreases with increased heel gap, the current cusp shown on the oscillographs should be less pronounced as the heel gap is increased. This effect is very noticeable in the oscillographs which are shown in the preceeding chapter.

Since the energy stored in the air gap is

$$W_m = wmA = \frac{B^2Ag}{2\mu o} \text{ joules.}^{1} \tag{10}$$

Where:

W_m = Energy stored in the magnetic field

wm = Energy per unit volume

A = Area of gap

g = gap length

If the force is kept constant and the air gap is increased by a certain amount dg, then the energy in the air gap is correspondingly increased.

$$dWm = \frac{B^2A\ dg}{2\mu o}\ .^{2} \tag{11}$$

However, in order to keep the force constant at the increased air gap setting the current must be increased to maintain the flux density B constant since,

$$F = \frac{B^2A}{2\mu o}\ .^{3} \tag{12}$$

We can therefore conclude that as the air gap is increased, the current increases proportionately where the magnetic material is not saturated and the μ is constant. Discounting the minimum heel gap setting which

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[1]Kraus, Electro-Magnetics, McGraw-Hill Book Co., Inc., New York, 1953, 1st ed., p. 265.

[2,3] Ibid.

obviously was affected by friction and binding, the above relationships are confirmed by Figs. 11 and 12. To summarize: the experimental data and the mathematical development supports the analysis that as the heel gap is increased, the operate current is proportionately increased.

Operate Time Compared with Heel Gap and Spring Tension

A study of Figs. 14 and 15 indicate that there is an increase in operate time as the heel gap is increased, but Figure 15 indicated some irregularities and it was decided that the analysis of this information would wait until the experimental data was obtained from relay #2. The experimental arrangement for relay #2 includes provision for obtaining armature motion time and it is felt that this type of information would be necessary in order to determine the energy relationships which might affect relay operate time. Accordingly, the analysis of this portion of the Thesis will be included in a subsequent chapter.

Release Time Compared with Change in Heel Gap

The curves which are shown on Fig. 15 indicate a fairly linear relationship between release time and heel gap setting for the higher armature spring tensions with the curve becoming less linear as the spring tension is decreased. The heel gap vs. release time for the armature tension of 75 grams indicates that as the heel gap is increased, the operation takes place near the bottom of the normal saturation curve where the μ of the ferromagnetic material changes sharply and the slope of the BH curve decreases. This would have the tendency to cause more random variation in release time with greater change in heel gap. See Fig. 21 for example of variation in flux with change in decaying mmf. It might be well to

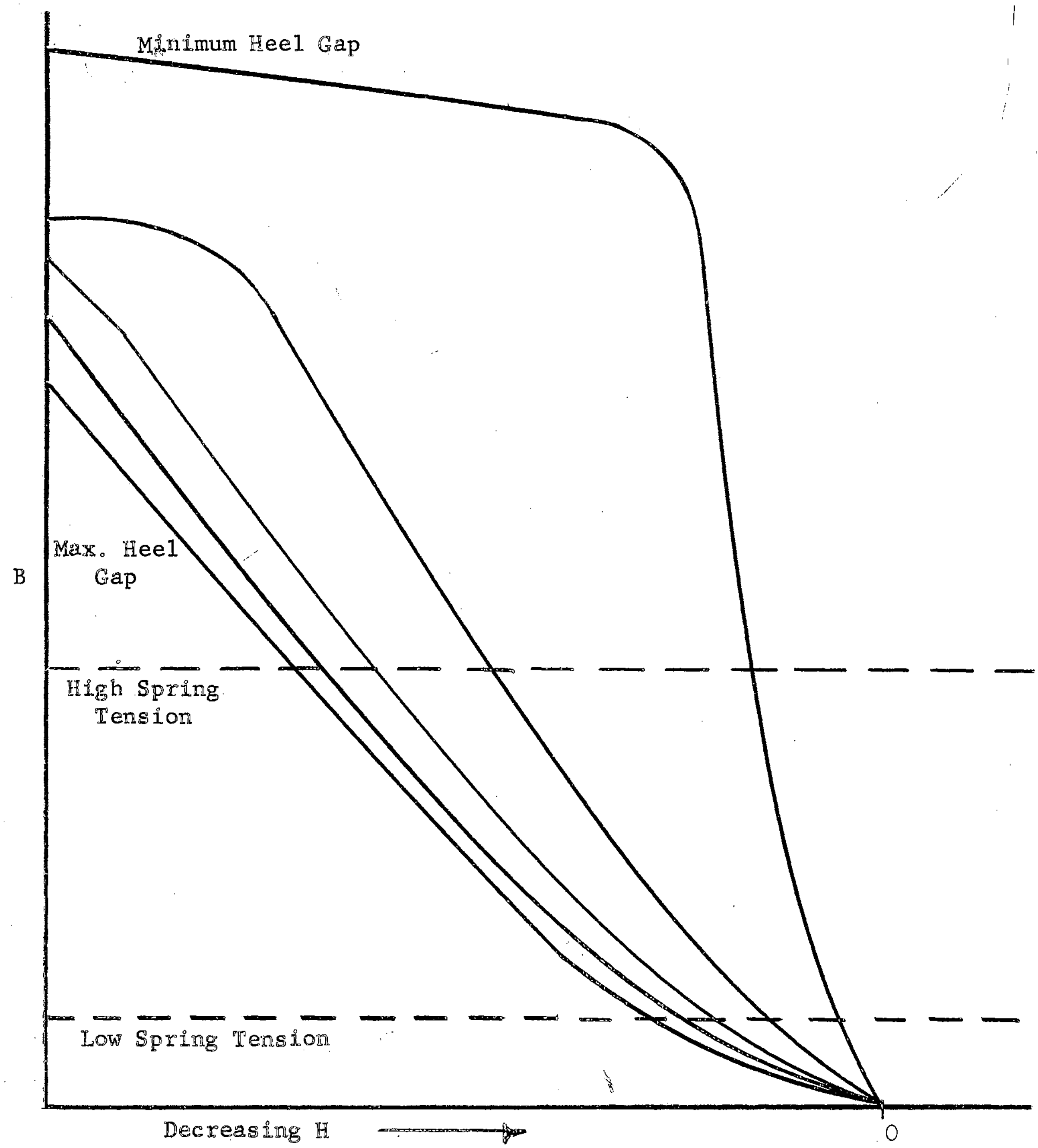


Fig. 21. BH Curves for Various Heel Gap Settings and Showing Typical Operating Points for High and Low Armature Spring Adjustments.

mention here that visual observations of the actual traces on the oscilloscope for a series of relay operations for both operate and release conditions revealed that often there is considerable variation in the traces for successive operations even though none of the conditions of applied EMF, armature gap, heel gap and armature spring tension were changed. These variations are random in nature and it is assumed that they are caused by the rather crude bearing supports for most relays. This unsatisfactory condition could be greatly minimized through use of precision ball or jeweled bearings. However these were not available for use in the experimental work which was done in connection with this Thesis.

Fig. 16 shows a similar set of curves, but with the armature operating air gap of .012" used. Many more points of operation or changes in heel gap were used in plotting this curve. A marked drop in release time is noticed near the heel gap setting which equals the armature air gap clearance. This may be caused by the decrease in angle of the armature with respect to the magnet pole face which occurs at this setting. This will be either confirmed or determined to be wrong from the results of the experimental data from relay #2. The possibility of any binding of the armature heel on the heel piece as the result of minimum clearance must also be considered when evaluating the information which is presented by the curves for the minimum heel gap setting.

When reviewing the flux vs the decaying mmf which is shown on Fig. 21, it should be realized that the probable curves which are shown result from a linear decay in the mmf. However, the circuit does not constitute a pure inductance and therefore the current decays at an exponential rate. This non-linear decay in current and resulting mmf is dependent on its rate of decay upon the inductance which is represented by the relay coil. For small heel gap settings where saturation may be reached, the decay for the saturated portion of the curve will be rather rapid because of the lower value of inductance which is presented by the relay coil for that period. Below the saturated portion of the same curve, the rapid decay in flux causes the coil to present the effect of more inductance and the decay of current becomes less rapid. It can therefore be seen that the decaying mmf rate will vary with time for each curve and, practically speaking, the point in time where the mmf approaches zero will be different for each curve. Therefore from the above discussion it can be seen that the various independent decay curves which result from their corresponding heel gap values make the analysis of the armature release results very complex. Because of the lack of equipment for measurement of instantaneous flux, the behavior of the relay for armature release conditions must be largely accepted from the information which is reflected by the results of the experimental data. This information is shown on the Figs. 15, 16, 17, 18 and 19. This information is summarized as follows:

1. As the heel gap is increased and the armature spring tension is kept constant, the armature release time at first increases and then decreases at values of heel gap which approximate the armature air gap value. As the heel gap is further increased, the release time again increases as the heel gap is increased, but subsequently decreases again at the highest heel gap settings. (See Fig. 16).
2. As the armature spring tension is increased, the

effects, which are described in the preceding item number 1 above, become less pronounced and the change in release time with increase in heel gap setting becomes more linear. (See Fig. 16).

3. As the spring tension is varied with the heel gap held constant, the release time decreases as the spring tension is increased.

4. At the lower spring tensions under the conditions which are described in the preceding item number 3, the change in release time with increase in spring tension is not linear, but as the spring tension is still further increased, the change in release time becomes more linear. (See Figs. 18 and 19).

Transfer of Mechanical Energy to Electrical Energy and How it Affects Release Time.

After the relay has been energized a finite amount of the original electrical energy is stored in the armature spring as potential mechanical energy. When the relay is de-energized, part of this energy is transferred back into the electrical circuit as the spring moves the armature away from the magnet pole face. This effect has the tendency to cause the current to increase in the relay coil and delay the decay of flux.

This causes the attractive force on the armature to decay more slowly and increase the armature motion time. The overall effect is to slow the operation of the relay on release. Since the normal saturation curve for the ferromagnetic material decreases in slope for lower mmf values and also decreases in slope for higher mmf values where saturation may be reached, armature release time with changes in spring tension for fixed values of heel gap will be non-linear. As the heel gap is increased the flux changes with time become more linear because of the modifying effect of the air gap with the overall effect of a more constant μ. This tends to make the release time more linear with change in spring tension as the heel gap values are increased. This effect is exemplified by the curves shown on Fig. 18.

Fig. 18 also shows that heel gap adjustment of .010" appeared to cause the resulting curve to cross over the higher heel gap setting curve at a particular spring tension and produce a reduced release time for all spring tensions below this value. It is noticed that this curve is for a heel gap adjustment which approximated the armature air gap setting. This cannot satisfactorily be explained. It is also noticed that there always seems to be a different behavior of the relay operation where the heel gap setting approximates the armature air gap setting. This behavior is observed for the operate as well as the release situation.

Inter-relationships Between Flux and Driving mmf, Current and Time in an RL Circuit, and Flux and Time in an RL Circuit.

Fig. 22 contains some typical curves which describe the relationships. Fig. 22a is the typical BH curve for a ferromagnetic material. Fig. 22b shows the current vs time relationships. From this figure the slope of the current vs time for a pure inductance can be seen to be a straight line with the slope decreasing with increase in L. As more R is introduced into the circuit the steady state current drops and the non-linear change of current with time becomes more pronounced. The introduction of R in the circuit modified the normal saturation curve with time as shown in Fig. 22c during the build up. Figs. 22d and 22e

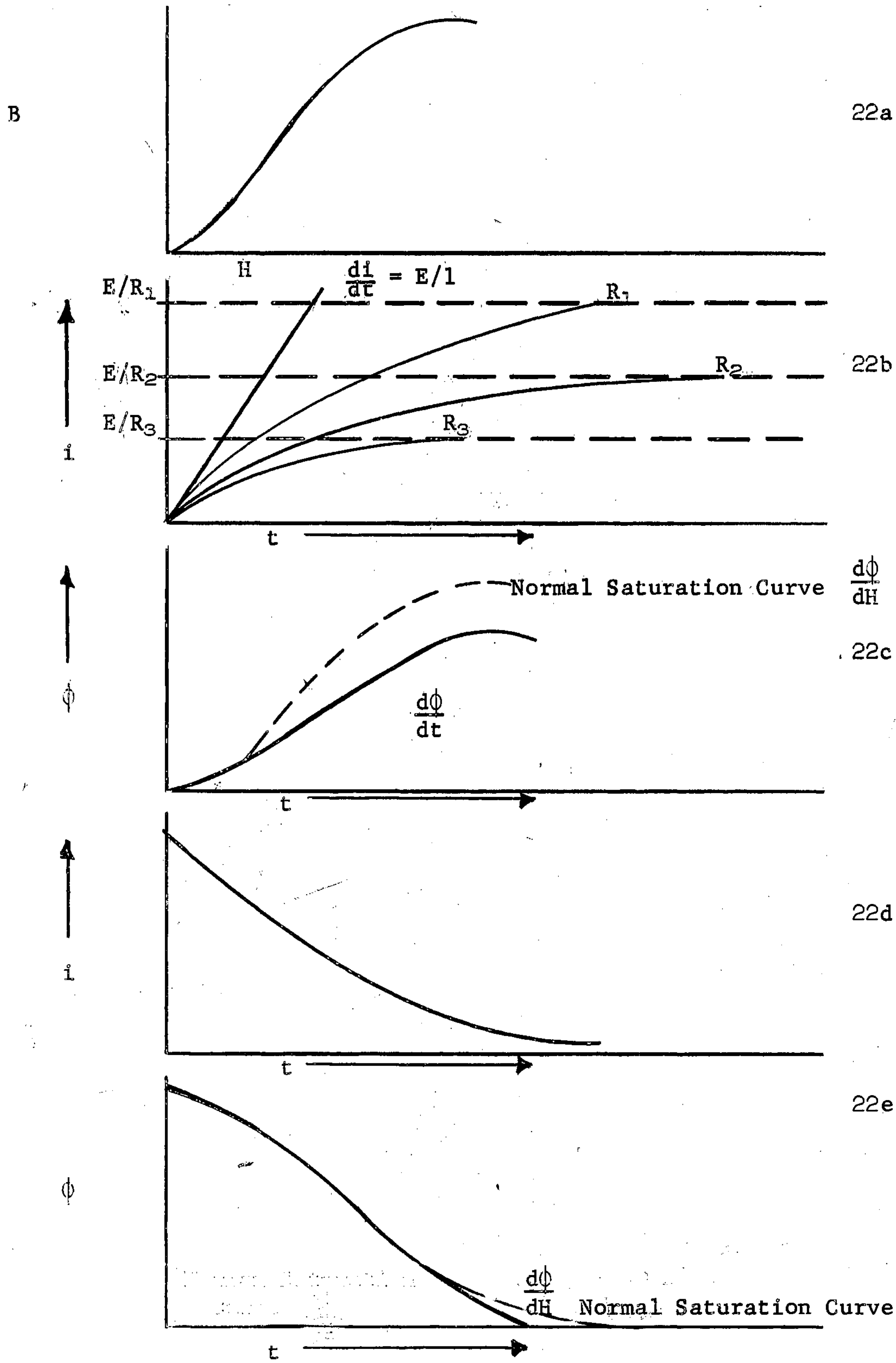


Fig. 22. Inter-relationships Between Flux vs Driving mmf, Current vs Time, and Flux vs Time in Rise and Decay with RL Circuit.

are similar curves for the current and flux decay in an RL circuit. These factors are inter-related and complicate the analysis. It can be seen however, that the net results will be non-linear and will combine to produce the results which were obtained experimentally.

General Comments or Conclusions on the Experimental Data From Relay #1

The analysis which is presented in the preceding chapters for the experimental data on Relay #1 is largely supported by the information as presented. However, the variations in the curves for heel gap settings which approached the armature air gap settings were provoking and it was considered necessary to obtain experimental data on a new relay which permitted changes in heel gap settings without changing the angle of the armature with respect to the magnet pole face. This was done by using a relay which permitted adjustment of the heel gap setting by sliding a portion of the heel piece itself. This arrangement eliminated the possibility of errors occuring for the reasons which are outlined above.

CHAPTER VI

EXPERIMENTAL RESULTS FROM RELAY #2

The experimental results from the second relay which was used are shown in the oscillographs on the succeeding pages of this chapter. The information which is shown on the oscillographs is plotted on curve sheets which are also included in this chapter. The results shown are quite self-explanatory as far as the information presented is concerned. The analysis of these results are included in the next succeeding chapter.

Armature Motion Time

As a result of the information obtained from the experimental data and the subsequent analysis of the first relay, it was decided that information on the armature motion time would be desirable in that such information might aid in the final analysis of the results. This was accomplished by modulating the electron beam of the oscilloscope as described in Chapter IV. The beginning of the armature motion time during armature closure is indicated by the beginning of the dark trace on the oscilloscope presentations in this chapter. The end of the armature motion closure trace is indicated by the dip in the current.

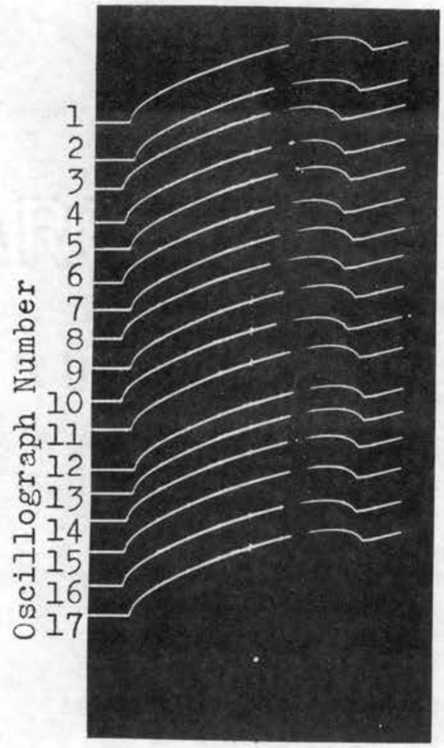
During armature release the end of motion only is indicated by the first blip. Since this thesis is primarily concerned with the effects of heel gap variation on the closure operation, no further modification of the circuitry was attempted to obtain the complete armature motion on release because of the excessive time and complication which would be required. The oscillographs shown on Figures 23, 24 and 25 show the armature operate time for the various heel gaps indicated and for the armature air gaps of .006", .012" and .018".

Operate Time

Figures 23 and 24 show complete operate trace showing the operate time and armature motion times vs the driving current. Figure 25 shows the complete operate and release traces for one experimental run with the heel gaps as indicated and with an armature air gap of .050". A curve sheet indicating the information obtained from the oscillographs is included in this chapter for convenient reference.

Relay #2 Coil #1

100 ohm discharge resistance
10 ohms shunt resistance
Coil voltage 36 volts
Steady state current 77 MA
Horiz. defl. 10ms/cm
Vert. defl. .1 v/cm
Armature air gap .018"
Armature spring tension 150 grams



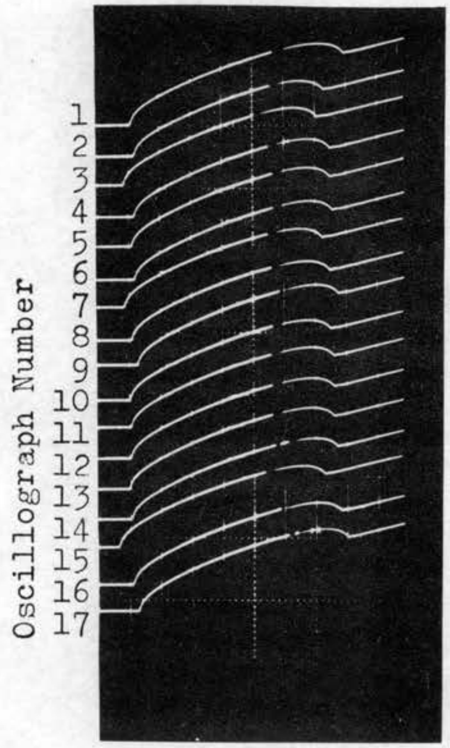
Oscillogram 17

Oscillograph Number	Heel Gap (inches)
1	.0015
2	.003
3	.004
4	.005
5	.006
6	.007
7	.008
8	.009
9	.012
10	.015
11	.020
12	.025
13	.035
14	.050
15	.070
16	.090
17	.100

Fig. 23. Current vs Time for Armature Air Gap of .018" and Heel Gaps from .0015" to .100"

Relay #2 Coil #1

1000 ohm discharge resistance
10 ohms shunt resistance
Coil voltage 36 volts
Steady state current 77 MA
Horiz. def. 10ms/cm 5X mag.
Armature air gap .012"
Armature spring tension 150 grams



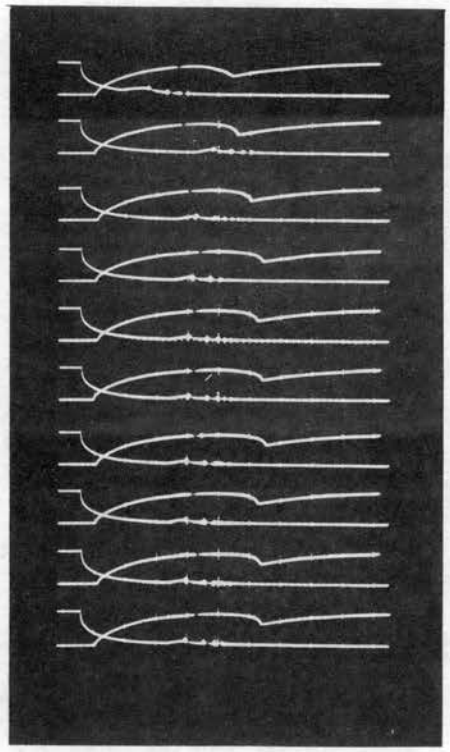
Oscillogram 18

Oscillograph Number	Heel Gap (inches)
1	.0015
2	.003
3	.004
4	.005
5	.006
6	.007
7	.008
8	.009
9	.012
10	.015
11	.020
12	.025
13	.035
14	.050
15	.070
16	.090
17	.100

Fig. 24. Current vs Time for Armature Air Gap of .012" and Heel Gaps from .0015" to .100"

Relay #2 Coil #1

1000 ohms discharge resistance
10 ohms shunt resistance
Coil voltage 24 volts
Steady state current 50 MA
Horiz. defl. 10ms/cm
Vert. defl. .5 v/cm
Armature air gap .050"
Armature spring tension 150 grams.



Oscillogram 19

Oscillograph Number	Heel Gap (inches)
1	.003
2	.010
3	.020
4	.030
5	.040
6	.050
7	.060
8	.070
9	.090
10	.100

Fig. 25. Current vs Time for Armature Air Gap of .050" and Heel Gaps from .003" to .100"

CHAPTER VII

ANALYSIS OF RESULTS FROM RELAY #2

The experimental results which were obtained from relay #2 generally paralled those which were obtained from relay #1 and therefore both sets of data will be used for analysis and conclusions.

In developing a working hypothesis an attempt was first made to correlate the current vs time curves for the relays with results of the test data. This led to some difficulty because this information within itself did not permit a clear presentation as to cause and effect. Since energy in the air gap is expressed as:

$$Wa = \frac{B^2 A\ la}{2uo} \qquad (4)$$

And since energy can be expressed as force times distance, then

$$F = \frac{B^2 A}{2uo} \qquad (2)$$

Because of these relationships and the obvious direct relationship between energy and force on the armature, it was felt that this method would more clearly explain the provoking change in the armature motion time which appeared in the experimental results. It was noticed that as heel gap was increased, a portion of the heel gap vs armature motion time (see Fig. 26) indicated a decrease in armature motion time. In an effort to satisfactorily explain this action, the product of the voltage across the inductance and the current through the inductance for an RL circuit was integrated over

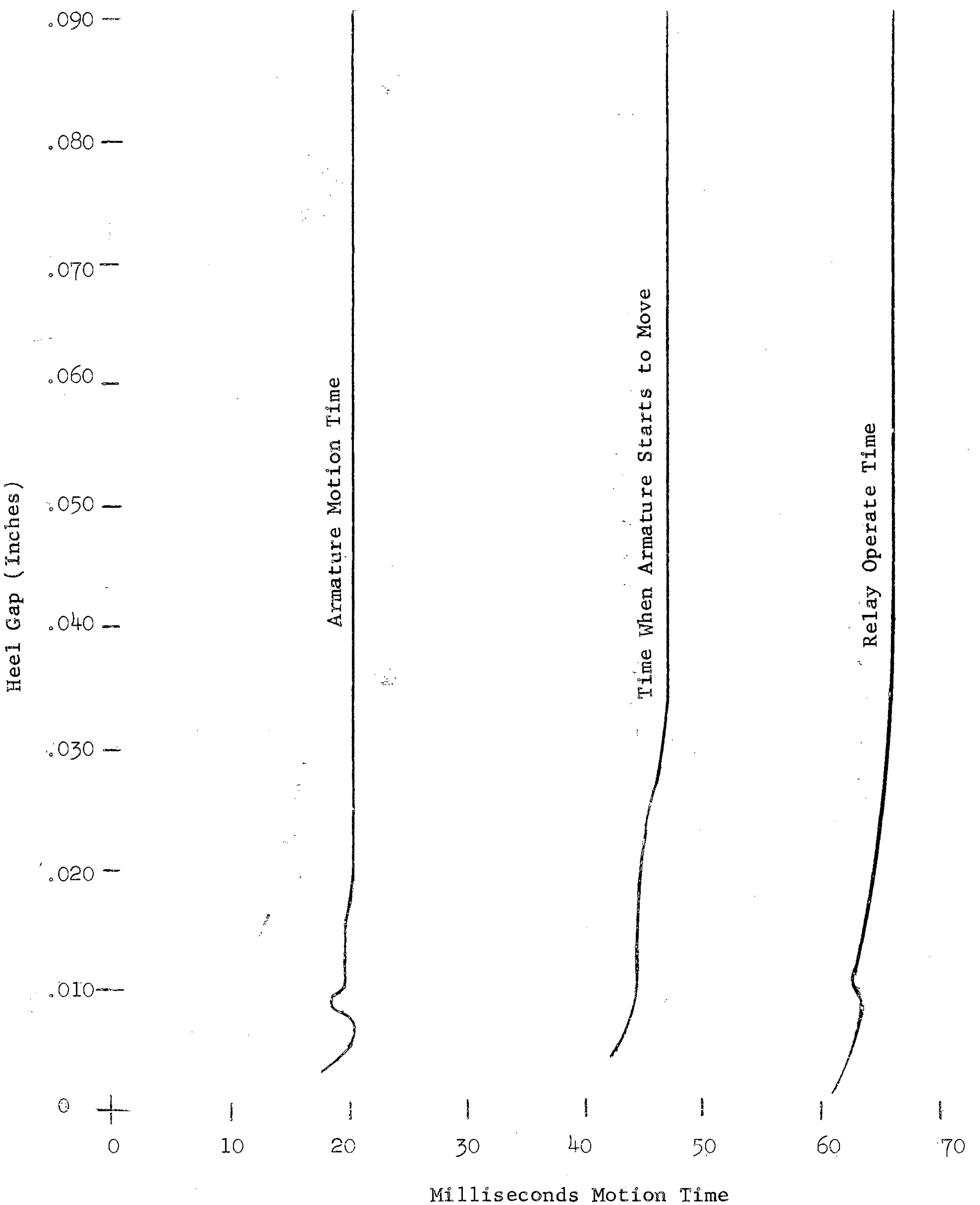


Fig. 26. Time Relay Starts to Move, Armature Motion Time and Relay Operate Time vs Heel Gap

the time to obtain an expression for the energy in the inductance. This expression was found to be:

$$W = \frac{LE^2}{2R^2} \left[1 - 2e^{-Rt/L} + e^{-Rt/L} \right] \qquad (12)$$

In order to simplify calculations an example of an RL circuit was used when R/L was unity. In this case R was considered to be 10 ohms and L to be 10 henries. This then reduced the working equation to:

$$W = \frac{LE^2}{2R^2} \left[1 - 2e^{-t} + e^{-t} \right]$$

or letting $\frac{LE^2}{2R^2} = K$, then:

$$W = k(1 - 2e^{-t} + e^{-2t})$$

Then for:

$t = 0;\ W = K\ (1 - 2 + 1) = 0$

$t = .01;\ W = K \left[1 - (2 \times .99005) + .98020 \right] = .0001K$

$t = .04;\ W = K \left[1 - (2 \times .96079) + .92312 \right] = .00154K$

$t = .08;\ W = K \left[1 - (2 \times .92312) + .85214 \right] = .0059K$

$t = .16;\ W = K \left[1 - (2 \times .85214) + .72615 \right] = .02187K$

$t = .32;\ W = K \left[1 - (2 \times .72615) + .52729 \right] = .07499K$

$t = .64;\ W = K \left[1 - (2 \times .52729) + .27804 \right] = .22346K$

$t = 1.28;\ W = K \left[1 - (2 \times .27804) + .08830 \right] = .52122K$

$t = 2.50;\ W = K \left[1 - (2 \times .0828) + .00674 \right] = .84114K$

Where $R = 10\ \Omega$; $L = 10H$ and $E = 50v$.

$K = 125$

The results of the above calculations were then plotted on a curve sheet and is shown on Figure 27.

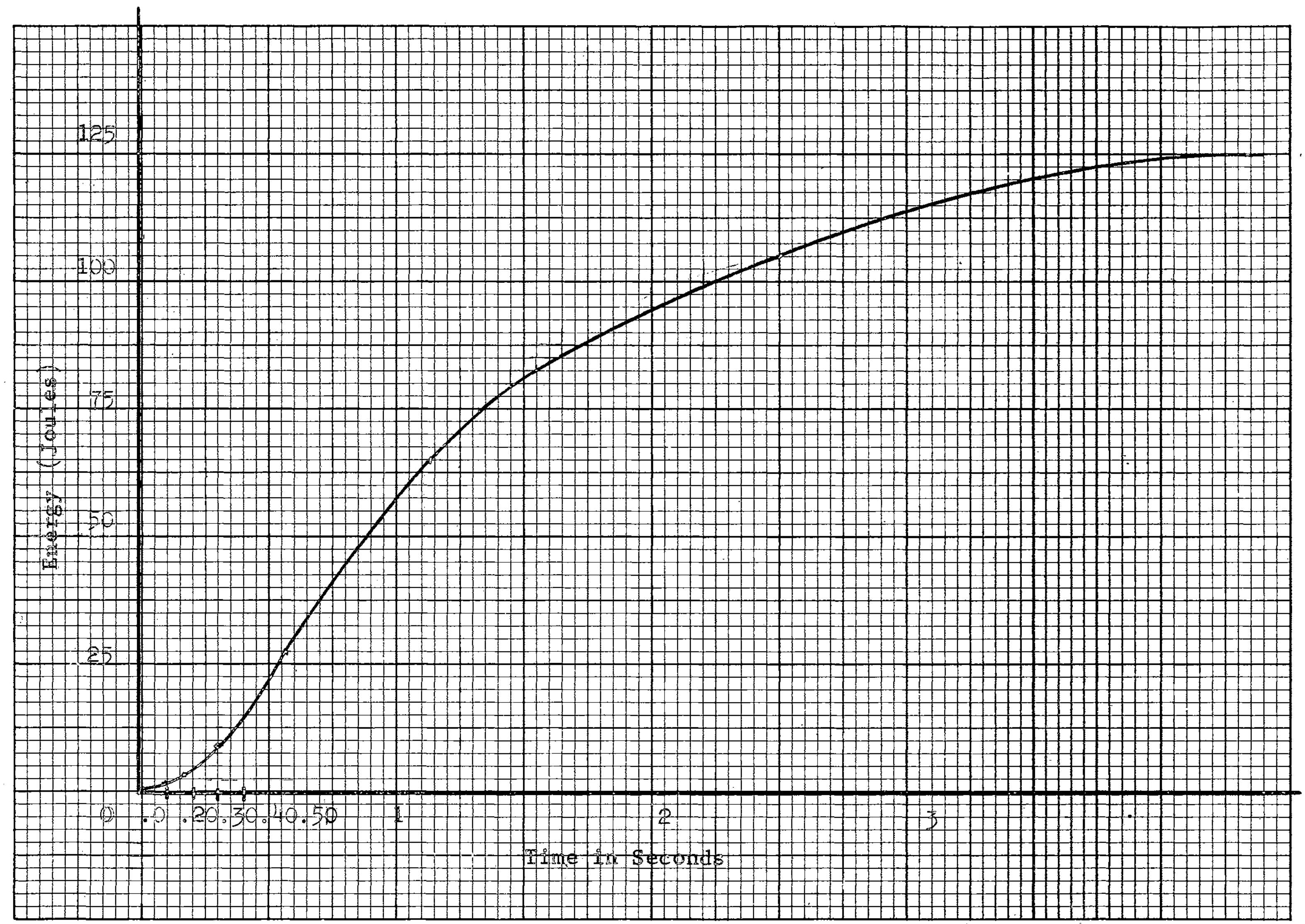


Fig. 27. Energy vs Time for an Inductance in an RL Circuit

From this curve sheet it can be seen that the slope of the curve undergoes change throughout the transient period. The slope represents the rate of change in energy with respect to time and it therefore seems reasonable to assume that the greatest force which is acting on the armature throughout its motion period would take place during the steepest slope portion of the energy vs time curve. Since energy is being pumped into the inductance at its greatest rate during this period and since the force on the armature is a direct function of energy as shown before, then it can be seen that the armature motion time will be reduced during this portion of the energy transient period. It can also be seen that as the inductance in the circuit is decreased, the transient period for energy build-up will decrease and affect the slope of the curve. The overall effect of decreased inductance when the heel gap is increased is to steepen the energy vs time curve somewhat, but decrease the total energy stored when steady state conditions are attained. It can also be seen that for each heel gap adjustment there is an optimum spring tension which will keep the armature from closing until the steepest slope is attained on the energy vs time curve. This relationship is clearly evident in the curves which are shown on Fig. 10. Even though armature motion starts later in time as the heel gap is increased, the armature motion time may be short enough under optimum adjustment of heel gap and spring tension conditions to reduce the entire operate time of the relay as the heel gap is increased until the optimum point is reached. From further study of the curves which are shown on Fig. 10, it is also evident that as the spring tension is increased the slope of the curve as plotted against heel gap variations is increased after the optimum point is reached. This condition can be correlated with the energy vs time curve. This curve indicates that as the spring tension is increased, the closure of the relay will take place at the upper less steep portion of the curve and the rate of energy increase during the armature operate period will be less than for the lower spring tensions. This condition therefore causes a greater spread of the curves at the higher heel gap settings as shown in the figure.

Additional Considerations Involving the Energy-Time Curve

By taking the derivative of the energy equation, the equation of the slope of the curve can be obtained and the slope for a series of different operating times can be calculated. It might be noted here that the slope of the energy curve represents the equation for power in the inductance (instantaneous). This method will permit calculations to be accomplished which will reveal the steepest part of the curve to determine the optimum operate point where armature motion should start.

For the armature motion during the optimum part of the energy-time curve as previously discussed, the significance of the greatly reduced armature motion time is quite obvious. It not only indicates that the accelerating forces must be much greater, but also for this reason the effects on contact bounce should be obvious. It appears that if the contacts make during a point of greater acceleration of the armature, less contact bounce is likely to result. This effect is not within the scope of this thesis however, and is mentioned here only as a thought. We can see from the discussion in this paragraph, that there is an optimum heel gap for best armature motion time and that this armature motion time will affect the operate time of the relay. We can also conclude that the armature motion time is dependent on the point or portion of the power vs time curve where the armature motion takes place.

Instrumentation

In analyzing the instrumentation which was used in determining the transient effects during relay operation, it became obvious that in general all information for a set of conditions must be obtained during each relay operation. For example; armature motion time and armature operate time must be recorded simultaneously. Recording each bit of information during successive operations will produce erroneous results because of the random effect in the operation of the relay. Successive operations of the relay under the same controlled conditions are not exactly alike.

Since the force acting on the armature as the result of the electrical circuit is a function of the energy in the inductance, then means of instantaneously recording the product of voltage and current over the time of the transient period would be very desirable. The author of this thesis believes that he has determined a method for doing this. The time which would be involved in designing and building the necessary equipment prevented its use in the experimental work connected with this document. It is however, mentioned here for possible use by future experimenters. Briefly, the scheme is as follows: the information on current in the relay circuit would be introduced into an amplifier. This current information would be obtained from the voltage variation across a resistor which is in series with the relay. By means of a pickup loop of wire around the relay coil, the voltage across the pure inductive part of the circuit would be obtained and this voltage would be used to vary the circuit voltages of the amplifier to vary the gain of the same amplifier from zero to the gain which is represented by the step voltage applied to the relay circuit. Since instantaneous power is the product of current and voltage, the output of the amplifier would be a function of this product. The output of the amplifier would then be used to vary the vertical deflection voltage of the oscilloscope against a time base on the horizontal deflection plates. Through this method the total energy used from t = 0 until the armature closes and subtracting from it the energy from the point where the armature just starts to move until it closes, the total energy used to move the armature can be found.

CHAPTER VIII

CONCLUSIONS

As the result of the analysis of experimental results from both relays, the following is concluded:

1. The pickup current where the armature just starts to move is advanced in time after the relay is energized as the heel gap is increased.

2. The operate current (the point where the armature just closes) increases in a fairly linear manner as the spring tension is increased with the slope of this line increasing with each heel gap setting as it is increased (see Fig. 12).

3. Each line described above in conclusion 2 represents an increased set of operate current values as the heel gap is increased.

4. The operate time of the experimental relays increased successively as the heel gap was increased for the lower heel gap settings, then decreased to a point where the heel gap settings approximated the armature air gap setting. From this point on, the operate time increased again in a fairly linear manner as the heel gap was further increased. (See Figs. 9 and 13).

5. The armature motion time increased as the heel gap increased for the lower heel gap settings and then decreased until a heel gap adjustment approximated the armature air gap setting. As the heel gap was further increased the armature motion time became fairly constant. There

appeared to be an ideal adjustment for shortest armature motion time. (See Fig. 26).

6. With spring tension held constant the release time decreased in a fairly linear manner as the heel gap was increased for high spring tensions. As the spring tension was decreased the line representing the change in release time with change in heel gap was displaced later in time and became less linear. The non-linearity took place at the lower heel gap settings and increased in non-linearity as the armature spring tension was decreased. (See Figs. 15 and 16).

7. It is believed that the armature motion time is a function of the rate of change of energy into the relay coil as the armature motion takes place. (See discussion in Chapter VII and Fig. 27).

SELECTED BIBLIOGRAPHY

Kraus, John D. *Electro-Magnetics*. McGraw-Hill Book Company, Inc. New York, Toronto, London.

Lago, Gladwin V., and Waidlich, Donald L. *Transients in Electrical Circuits*. The Ronald Press Company, New York.

Stratton, Julius A. *Electro-Magnetic Theory*. McGraw-Hill Book Company. New York and London.

VITA

Charles C. Mack

Candidate for the Degree of

Master of Science

Thesis: AN INVESTIGATION OF THE EFFECTS OF THE VARIATION OF HEEL GAP ON THE PERFORMANCE OF ELECTRO-MECHANICAL RELAYS

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Millinocket, Maine, 18, July, 1920 and lived there until 1939.

Education: Graduated from George W. Stearns High School at Millinocket, Maine in 1937; attended the Evening Division of Northeastern University in 1941; graduated from United States Army Air Corps Flying School at Craig Field, Selma, Alabama on 5 August, 1952; graduated from Armed Forces Tactical School in 1944; graduated from Aircraft Maintenance Officers School at Chanute Field Illinois in 1945; completed a course in J-33 Turbo Jet engines at the Allison Division of General Motors, Indianapolis, Indiana in 1947; attended University of Maryland Overseas Extension School at Keflavik Iceland, 1954-55; received the degree of Bachelor of Science in Electrical Engineering at Oklahoma State University, Stillwater, Oklahoma. January 1959.

Professional Experience: Worked in the Receiving Tube Design Department of the Raytheon Production Corporation, Newton, Massachusetts during the summer of 1941, entered the Army Air Corps in December of 1941 as an Aviation Cadet; held assignments as a Fighter Pilot and Fighter Intercept Controller during World War II; was Aircraft Maintenance Officer at Mitchell Air Force Base in 1945, later was assigned as Jet Maintenance Officer for Headquarters Air Defense Command and Headquarters Continental Air Command; in 1948 received an assignment as Airbourne Radar Officer for the Air Defense Command; from 1949 to 1952 was assigned to Headquarters United Stated Air Force at the Pentagon as the Chief of the MARS Program, was the Signal Officer for Air at the Iceland Defense Force Nato Headquarters at Keflavik Airport Iceland from 1952 to 1955, during this period also was a member of the European Radio Frequency Allocation Panel; was later Chief of the Communications Systems Division at Headquarters Air Training Command, Scott Air Force Base, Illinois until 1957; held Amateur Radio Operators License since 1935 and currently hold an Amateur Radio Operators License Extra Class, Student member of AIEE, IRE, Eta Kappa Nu, Sigma Tau, Alpha Pi Mu; holder of Commercial Pilots License with Instrument Rating; currently Pilot/Major, United State Air Force.