HUNTING AND ITS CURE IN A PRECISION DYNAMOMETER AUTOMATIC TORQUE MECHANISM

Thesis by

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Harold L. Levinton.

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INTRODUCTION

This thesis deals with the problem of eliminating hunting in the precision dynamometer torque mechanism of the Hydraulic-Machinery Laboratory of the Metropolitan Water District of Southern California at the California Institute of Technology, and its solution by apparatus built by and from plans proposed by the author.

In addition to solving the particular problem here-in presented, the author, as part of his duties as a member of the laboratory staff, designed and built other apparatus for use in the laboratory. Some of these devices were built purely as experimental apparatus, while others were incorporated as permanent and necessary additions to the laboratory equipment. The following examples will serve as illustrations. The contacts of the automatic precision pressure gauges and venturi manometer required too frequent maintenance due to the delicacy of the instruments and the currents necessary for the contacts to control. A device using eight vacuum tubes solved this problem. It was desired to have a visual check of the laboratory "constant" frequency against a known standard radio station frequency. By utilizing a cathode ray tuning device such as the popular radio "Magic Eye", an instrument was designed and constructed which showed deviations in frequency from zero cycles per second upwards.

It is felt by the author that the following pages describing the elimination of dynamometer hunting show the manner in which he attacked and solved those problems presented to him.

REASONS FOR BUILDING LABORATORY

The Metropolitan Water District of Southern California in its operation of the Colorado River Aqueduct will pump 1500 cubic feet of water per second (about one billion gallons per day) over several mountainous regions requiring a total lift of nearly 1700 feet. This will be done at five pumping plants with average lifts varying from 146 to 444 feet in height.

The total installation consisting of nine pumps at each plant (eight operating pumps plus one spare unit) will be powered by electricity from Boulder Dam at a cost of some $5,000,000 per year. Obviously, any increase in efficiency will represent a considerable saving in operating costs; or, to be more specific, a one percent change in efficiency represents about $50,000 a year in the cost of electricity alone. To this must be added the effects on installed plant size and costs.

In an endeavor to secure further knowledge of those characteristics which would give its pumps a maximum of simplicity, reliability and efficiency, the Metropolitan Water District built on the campus of the California Institute of Technology, at Pasadena, a hydraulic machinery laboratory of unique design.

BASIS OF LABORATORY DESIGN

The principle ideas back of the entire design were:

1. All instruments were, if possible, to be calibrated in terms of fundamental units, units of length, mass, and time. The one exception to this being the Venturi Tubes used to measure the quantity of water flowing; these were secondary standards which depended on volumetric measurements for their calibration, but could be calibrated in place at any time with comparative ease.
2. Measurements of all quantities involved, Speed, Torque, Quantity, Suction Pressure, and Discharge Pressure were to be made simultaneously and with an accuracy such that the final results would have an error no greater than one-tenth percent.
3. The laboratory should be flexible so that pumps of any speed, quantity, suction head requirements, or discharge head development could be tested at their exact ratings; also both single and double suction pumps were to be tested.

A survey of the field showed that commercial instruments to fulfill the requirements of the laboratory were not available, so it was necessary for the laboratory staff to develop its own instruments which were then specially made to order by local instrument makers.

DESCRIPTION OF THE LABORATORY AND APPARATUS

Except for the speed, all quantities are "weighed", which means that they are registered on the equivalent of a "dead weight tester", or a beam balance. Pressures are measured on instruments such as are shown in Figure 1. The quantity of water flowing which determines the differential pressure across the venturi tubes is measured by a similar instrument modified to read the differential pressure; these readings plotted against true quantity as measured by the volumetric tanks for accurately timed intervals may be used to plot a curve of Venturi Gauge Readings against True Quantity. Temperature correction causes this calibration to take the form of a family of curves each of which is for a fixed temperature.

The torque is measured on a "cradle type" electric dynamometer in a manner similar to that of the pressure gauges. The operating principles of the torque measuring device are illustrated in Figure 2. The sensitivity of the dynamometer is of the order of 2-3 hundredths of a pound-foot with a total scale of over 800 pound-feet.

The instruments all have one feature in common. Each has a system of coarse adjustments with the "in-between" points obtained by a motor operated sliding weight moving on a calibrated beam. The entire group of these motors is

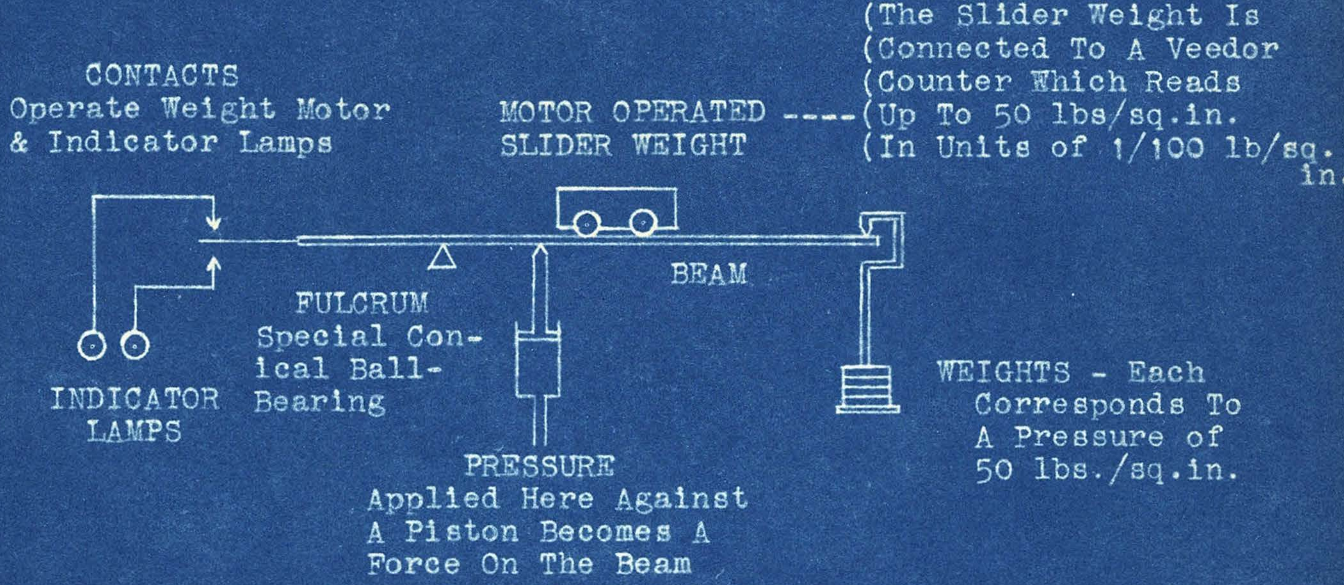


FIGURE 1

SIMPLIFIED PRESSURE GAUGE

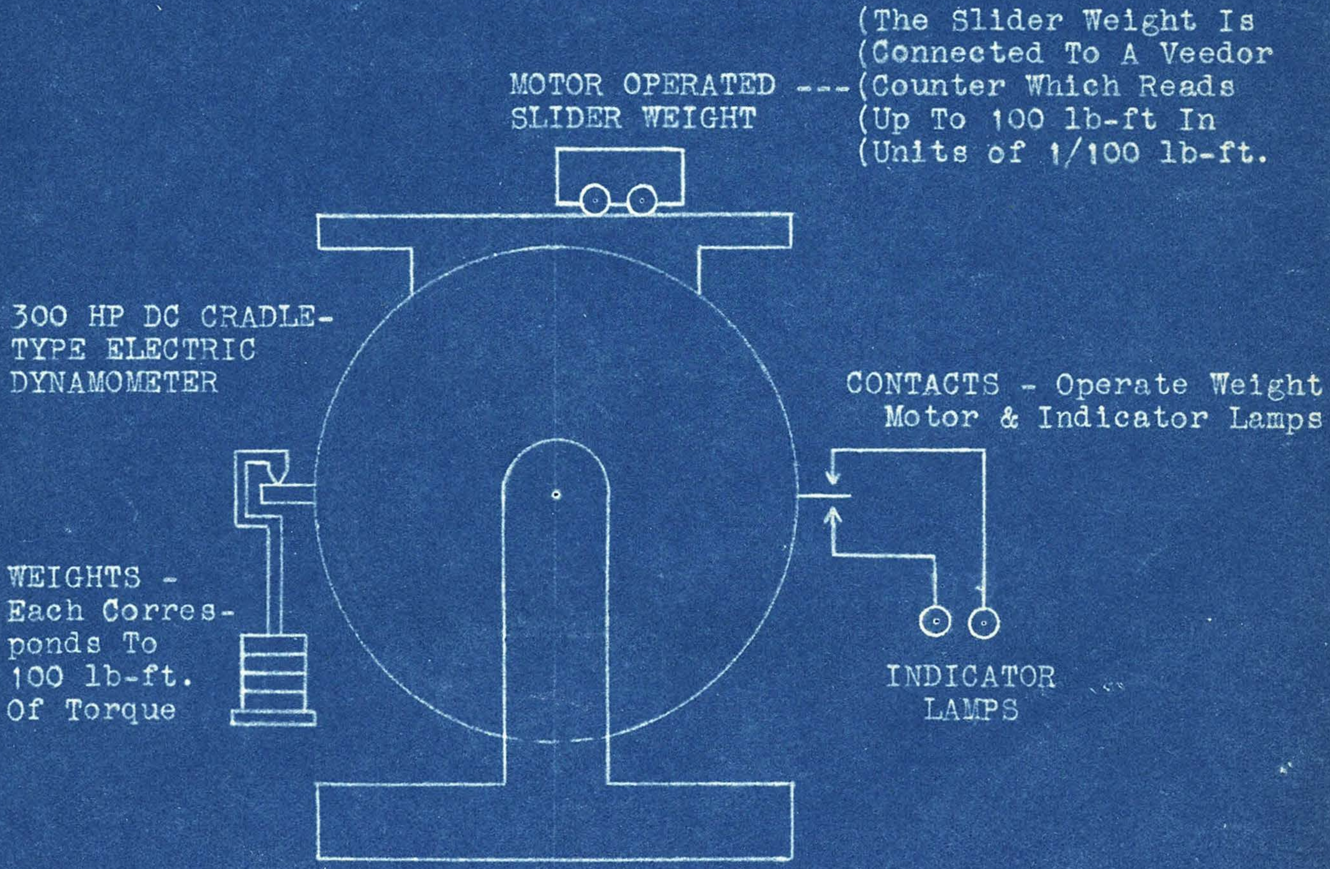


FIGURE 2

SIMPLIFIED TORQUE MECHANISM

controlled from a single master "Balance Switch". For a given set of conditions the test operator snaps the switch "On". The weight motors operate, causing the various beams to balance, which condition is indicated by lamps suitably connected to each instrument. Off balance in either direction lights one or the other of the two lamps on each instrument; at balance the lamps are either both out or alternately flashing due to vibration. Simultaneous balance of all instruments means that all quantities are correctly measured for the particular operating condition established. The operator then snaps the balance switch "Off", preventing the sliding weight motors from moving if any disturbance occurs in the system. He then records the instrument readings at his convenience, after which the conditions of flow are changed and the process repeated.

The speed of the dynamometer and the pump which it drives can be pre-set and maintained by an electro-mechanical device. In this device a small synchronous motor, whose constant speed is fundamentally determined by a piezo-electric quartz crystal oscillator, is used as a standard of comparison. This constant speed motor is coupled to one side of a differential. A second synchronous motor, whose speed is determined by a synchronous generator on the dynamometer shaft, is coupled through four sets of decade gears to the other side of the differential. The decade gears are so arranged that when the dynamometer runs at the particular speed for which the gears are set, the side of the differential driven by the dynamometer controlled synchronous motor runs at the same speed as the side driven by the constant speed motor. Under these conditions the shell of the differential will not turn. Any inequality in speed of the two sides of the differential causes the shell to rotate one way or the other, according to whether the dynamometer is faster or slower than the speed for which the decade gears are set. Movement of the differential shell affects a unit controlling the field rectifier tubes, changing the field current of the dynamometer which, being a D.C. machine, changes its speed accordingly to the correct speed as indicated by the decade gears. The decade gears are so constructed that speed selection between 500 rpm and 5500 rpm is possible in one-half rpm steps. The speed selected is maintained constant with instantaneous variations of only plus or minus one rpm as measured with an oscilloscope.

These brief descriptions of the instruments do not give credit to the designers' ingenuity in solving the many problems arising regarding the maintenance of sensitivity of the instruments, which in turn required negligible friction effects and the rapid operation of balancing and speed correcting devices. Each instrument is worthy of a paper in its own right, some of which have already been or are in the process of being written. (See Nov.1936 Transactions of the A.S.M.E.) The results obtained in the laboratory, however, through approximately two years of testing showed that these problems have been successfully solved. For the first time, centrifugal pump characteristics have been determined to an accuracy of one-tenth percent, or from ten to twenty times more accurately than here-to-fore, while the time required for testing was decreased to about one-tenth the usual time required.

Needless to say, all was not fair sailing at first. As with all new designs, many troublesome "bugs" appeared in which was required considerable skill on the part of the laboratory staff for their elimination. The problem with which this paper is concerned, while not the most troublesome, is indicative of those encountered, and is one which the author had a personal interest in solving.

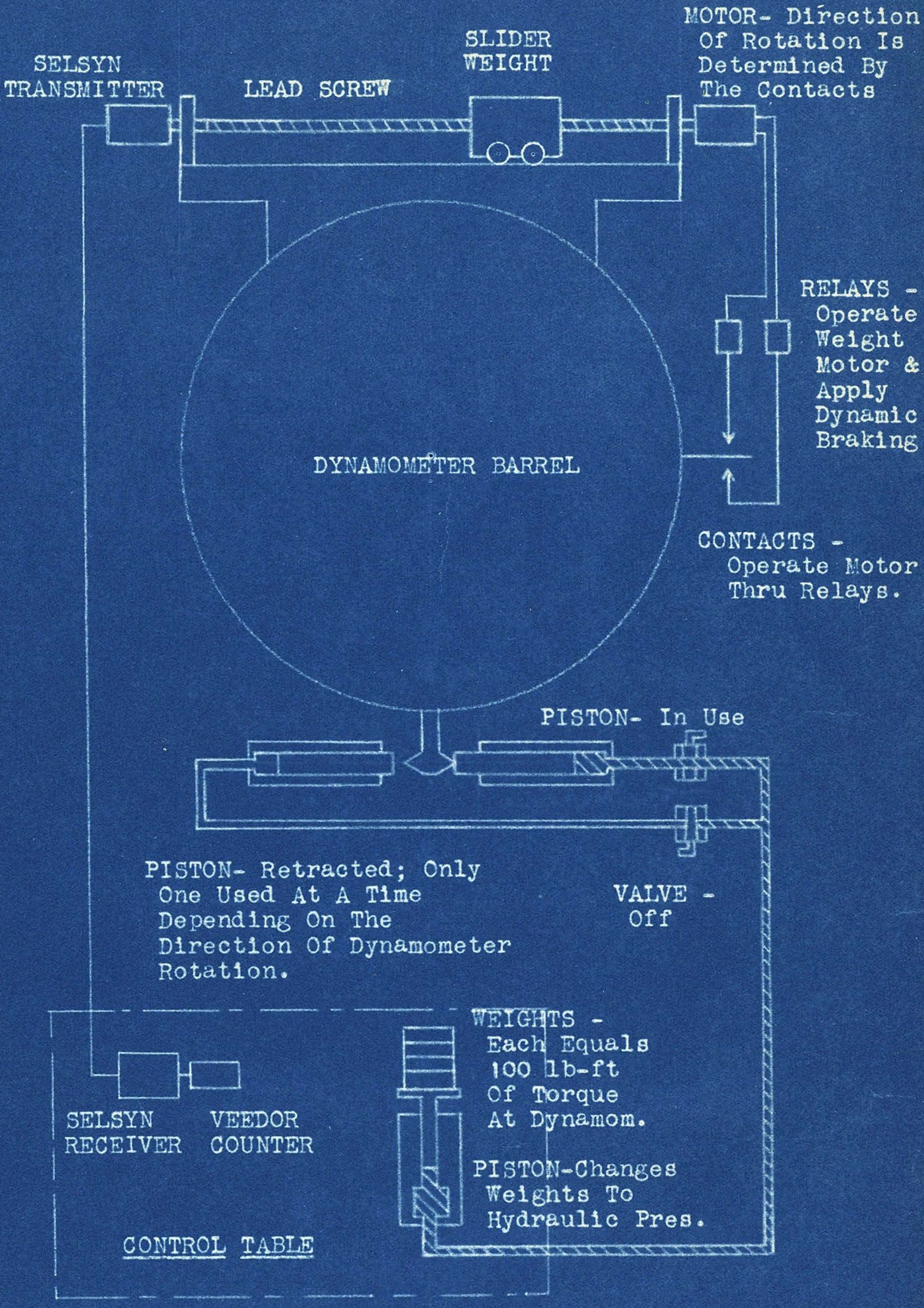
THE PROBLEM

The problem was that instead of coming to a balance the dynamometer torque mechanism would "hunt" between its contacts, causing the sliding weight to move through a cycle of several pound-feet. Since it was desired to measure down to one-tenth pound-foot or better, this was a serious limitation which required correction before automatic operation of the entire laboratory could be attained. Until such time as the automatic balance was achieved, the dynamometer was balanced manually by one of the test crew; the sliding weight motor being energized by two push-buttons on the control desk until the indicator lights showed the torque to be balanced. Manual balancing took from two to three times as long as the automatic balancing after it was perfected.

SOLUTION OF THE PROBLEM

Figure 3 shows the basic principles of the installation. The large torque weights on lever arms shown in Figure 2 are replaced by a hydraulic system which permits the equivalent of weights on levers to be applied by weights at the operating desk so the operator need not leave the controls in order to change weights. For the increments between weights, the slider weight is used. This is motor driven through a lead-screw so proportioned that a "Veedor" counter geared to it reads in 1/100 of a pound-foot. A similar counter located at the operating desk is actuated by a "Selsyn" transmitter and receiver. Originally, the slider motor was actuated by a set of relays operated directly by a set of contacts on the dynamometer. These contacts were connected to the master balance switch so the motor was de-energized when the switch was "off". With this set-up the dynamometer was supposed to be self-balancing; however, in actual operation it was found that the dynamometer would not balance, but would "hunt" between the contacts with a period represented by plus or minus one to two pound-feet!

After studying this phenomena the conclusion was reached that the hunting was initiated by minute variations



COMPLETE TORQUE MECHANISM.

FIGURE 3

in the hydraulic system which could not be prevented. It seemed apparent that if the effect of these variations could be kept from reaching the contacts the hunting would cease. In other words, what was apparently needed was a dash-pot which would prevent small disturbances from closing the contacts, but at the same time would not prevent their opening, as this would interfere with the sensitivity of the instrument. If contact operation was always only in one direction this device would be simple and easy to make, but the contacts operate in two directions which are opposite, hence "one-way" standard dash-pots are impossible. Furthermore, mechanical dash-pots consume energy from the system which, in the balanced position of the dynamometer, would introduce a restraint which would affect its sensitivity. It was desirable that, when balanced, the dynamometer should be "free" from any external effects.

Further study brought the idea that the one-way dash-pot might be incorporated in the electrical circuits. Since only one contact could be on at a time, a dash-pot arranged to operate in the electrical circuits of that contact would in no way affect the dash-pot in the other circuit. In this way one-way dash-pots would be selectively effective for both directions of movement of the dynamometer barrel. Furthermore, such dash-pots would not consume energy from the system or provide restraint at balance since both contacts would then be clear and de-energized.

Two methods of obtaining time delay in electrical circuits are:

1. Changing the flow of current through an inductance.
2. Changing the flow of current through a capacitance.

Since inductances are usually physically larger than capacitors for effects of a like magnitude, and because capacitors can be more easily obtained in a multitude of values, the latter were chosen for the work.

Since small components were desired, and the time constant of a capacitative circuit depends on resistance as well as capacitance or on the R/C relationship, small capacitors could be used if the resistances associated with them could be kept high. High resistance in a small size means low currents. Low currents to be used to affect the slide weight motor circuit -- or low currents to affect high current circuits! Obviously a case for relays.

Mechanical relays operating on minute currents are delicate and expensive, but electrical relays or vacuum tubes are dependable if properly used, and if radio tubes are suitable as such relays they are cheap. Investigation brought forth that the Biology Department on the campus used such a device equipped with type 45 radio tubes in a circuit as is shown in Figure 4. With the contacts open, the tube is biased to "cut-off" and no plate current flows. Closing the contacts removes all bias and the tube passes current through the plate circuit, energizing the coil of an inexpensive relay and completing the operation initiated by the contacts in the grid circuit of the tube. Experimentation with a number of different types of tubes showed that the "45", being very rugged, dependable, easy to obtain, and cheap, was probably the best tube to use for the purpose.

A little research resulted in the circuit of Figure 5. This circuit has the property of permitting current flow as soon as the contacts are closed, and at the same time introducing a delay in stopping the current when the contacts are opened. Examination of the circuit will show that when the contacts close, the top plate of the capacitor quickly assumes a positive charge because the circuit is completed through the low resistance of the contacts. Opening the contacts immediately raises the tube grid positive, so that the tube continues to conduct. Meanwhile, the capacitor slowly discharges through the high

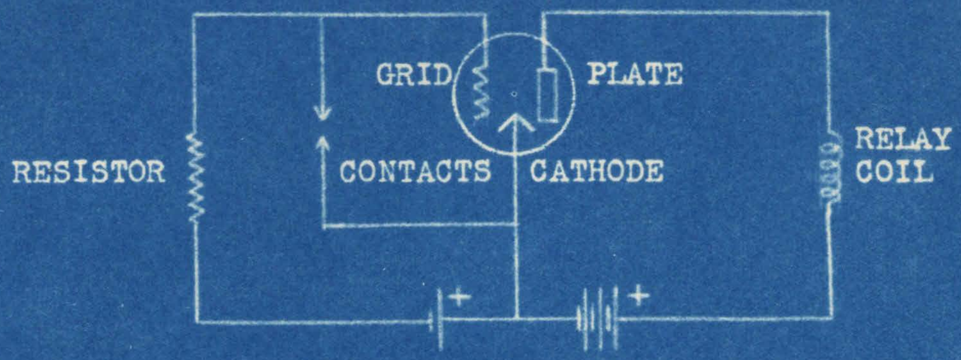


FIGURE 4

BIOLOGY DEPARTMENT VACUUM TUBE CONTROL CIRCUIT

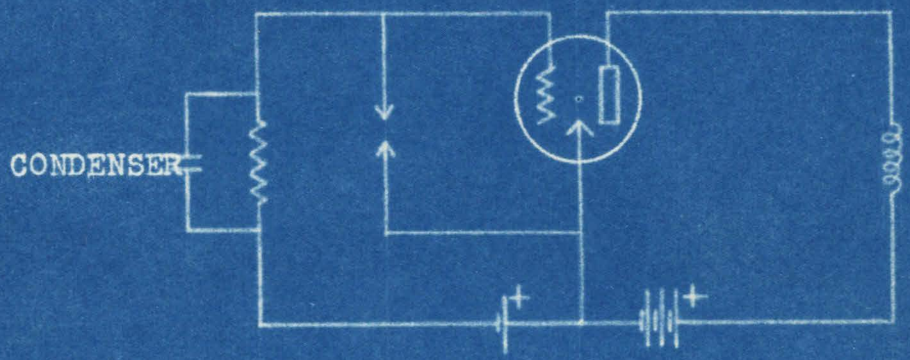


FIGURE 5

BASIC ONE WAY TIME DELAY CONTROL CIRCUIT

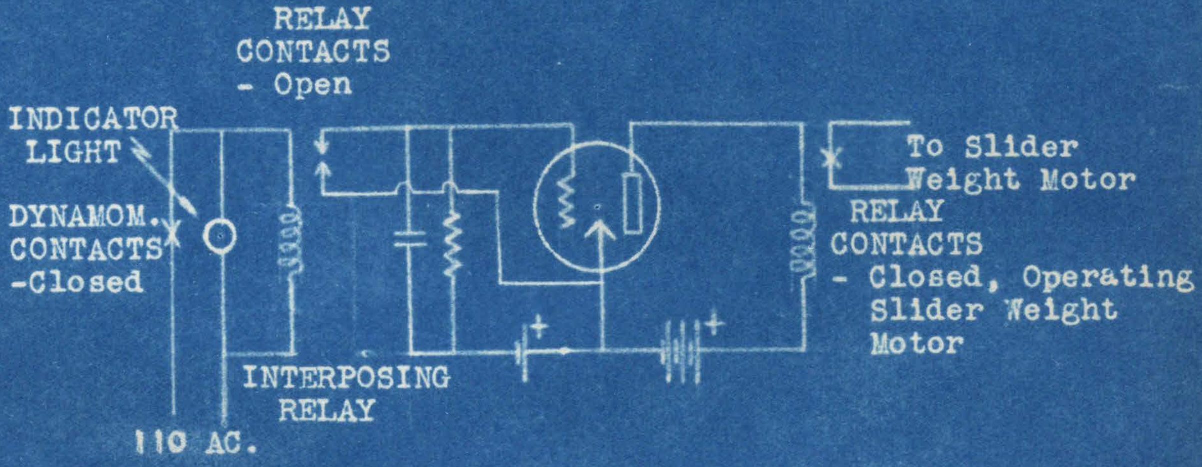


FIGURE 6

TIME DELAY CIRCUIT APPLIED TO TORQUE MECH. CONTROL grid-leak resistor, after which it charges in the reverse direction so that the top plate builds up a negative potential until it reaches a value such that the grid which is connected to it begins to decrease the flow of plate current and finally stops it entirely. Summarizing the effects:

1. Closing the contacts gives immediate results.
2. Opening the contacts gives delayed action.

The characteristic desired is the reverse of this, namely:

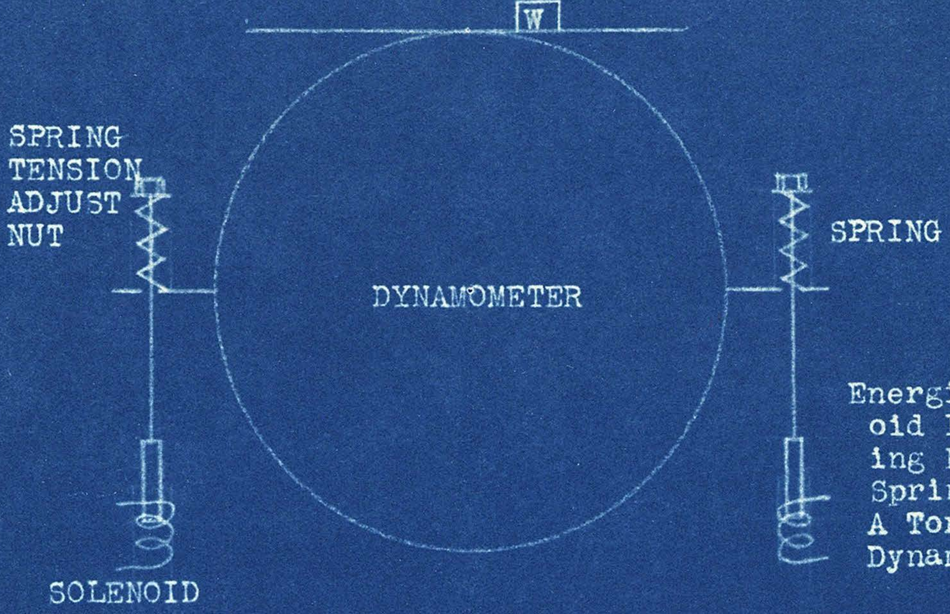
1. Closing the contacts should give delayed action.
2. Opening the contacts should give immediate action.

The use of an interposing relay with reversed contacts, as shown in Figure 6, solved this difficulty. Closing the dynamometer contacts energizes the interposing relays which opens its contacts placing the resistor-capacitor combination into the grid circuit. Following the delay caused by the discharging and recharging of the capacitor, the grid bias reaches a value sufficient to reduce the plate current to a point where the operating coil of the motor relay can no longer keep its contacts open; these now close, causing the slide motor to operate and move the weight in a direction to balance the dynamometer. When balance is reached the dynamometer contacts open, de-energizing the interposing relay, which closes its contacts and immediately removes the grid bias, thereby allowing full plate current to pass through the motor-operating relay. This causes its contacts to open, stopping the slide weight motor. A set of interposing relays and tubes applied to each dynamometer contact gives this control in both directions of dynamometer unbalance without removing energy from the system nor applying restraint to the dynamometer, which is what was desired. It should be pointed out that when the motor relay contacts open they not only remove the supply current from the motor, but they close another circuit through the armature to apply "dynamic braking" which very rapidly stops the motor. This helps prevent over-travel of the slider weight.

An experimental model of the delay mechanism was made. It was found that a 4 mfd. capacitor shunted by a variable resistor gave good results -- for each 500,000 ohms of resistance, a delay of about 1/3 second was obtained. A ten point switch enabled a total time of three seconds in 1/3 second steps to be secured.

The unit was connected to the dynamometer and the balance switch operated. The dynamometer came to balance, and then started hunting! Not as badly as before, through a cycle of only three- to four-tenths of a pound-foot, but never-the-less it was hunting. Apparently the diagnosis of the trouble was not entirely correct; only a partial remedy had been applied.

Further investigation of the action of the torque mechanism let to the following conclusions: Before the dynamometer contacts could open the slide weight must have reached, or slightly passed, the balance point; also, before the motor stops it moves the weight a little further, even with dynamic braking. These effects coupled with any friction losses, etc., all add together to cause the slide weight to overshoot balance by the equivalent of a few tenths of a pound-foot, causing the dynamometer to hunt back and forth through balance. Contacts which could "anticipate" balance would solve this difficulty as they could de-energize the slide weight motor in ample time before balance to counteract the bad effects outlined above. The construction of the contacts and the required dynamometer sensitivity precluded the use of true anticipating contacts due to the close clearances involved; the contacts were set at from one to one and one-half thousandths of an inch. However, the suggestion was made that the contacts might be "tricked" into acting like anticipating contacts if during the time that the slide weight motor operated a small torque was applied to the dynamometer in the same direction as that which the slide weight was attempting to make correction. This would cause the contacts to open in advance of actual balance by the amount of this extra torque which could be adjusted to just correct for the over-travel of the slide weight. An experimental device was made consisting of solenoids operating through springs to apply a pull on the dynamometer as shown in Figure 7. The solenoids were operated by sets of contacts on the relays operating the slide weight motor. Tests were again made, and the dynamometer came to balance repeatedly within plus or minus 1/100 of a pound-foot, or well within the accuracy desired! These tests were made with static weights hung on the dynamometer. Next, the equipment was tested under actual operating conditions and the dynamometer still balanced itself, but not quite as perfectly as before. It hunted about balance through plus or minus 3/100 of a pound-foot, apparently due to small variations in flow, vibration, etc. However, the sensitivity and accuracy were now well within the range desired and further correction was not required. During operation of the dynamometer it was noticed that occasionally the slide weight would suddenly move through a range as much as a pound-foot and then return to the original balance, or it might even return to a new balance point. Investigation showed that each of these excursions was followed by a similar change in



Energizing Solenoid Pulls Adjusting Nut Down on Spring Applying A Torque To The Dynamom. Barrel.

FIGURE 7

EXPERIMENTAL TORQUE "ANTICIPATOR"

SIMPLIFIED PERMANENT TORQUE ANTICIPATOR
FIGURE 8

the pressure measuring instruments and then by the venturi manometer. This indicated that the flow in the system had undergone some disturbance which was first made evident at the torque measuring device since it was nearest the pump, next it was detected by the pressure gauge a little way "down stream" from the pump, and lastly by the venturi tubes which were most remote from the pump. Thus, it was quite evident that the torque mechanism was actually giving a true picture of what was taking place in the hydraulic system. The solution to the problem having been reached, all that was necessary was the building of the apparatus in a permanent form. Actually, due to lack of time, the delay mechanism was never rebuilt. The experimental model was put into service and operated for about eighteen months until the completion of the pump tests with but a small amount of maintenance. The solenoid "anticipator" was rebuilt into a more simple trouble-free form. Instead of operating through springs, the solenoid was made to operate directly through the dynamometer by means of magnetic coupling. The amount of solenoid pull exerted was varied electrically by changing the current through the solenoid windings. This current was supplied by a tapped autotransformer which enabled the solenoid voltages to be independently varied from 30 to 130 volts. The manner in which the solenoids were coupled to the dynamometer is illustrated in Figure 8.

The complete schematic diagram of the device is shown on Figure 9. The dynamometer contacts directly operate the interposing relays and the neon indicator lamps. When one of the dynamometer contacts closes it energizes one of the interposing relays which in turn opens its contact. This applies grid bias to the associated V-2 vacuum tube through the delay circuit as previously explained to finally change the tube plate current sufficiently to de-energize the corresponding motor operating relay coil (these relays are shown in the energized position in Figure 9). The contacts then change position to operate the slider weight motor and the solenoid coils. On reaching what it feels to be balance, the dynamometer opens its contacts, de-energizing the interposing relay which closes its contacts. Grid bias is removed from the V-2 tube which immediately passes plate current to energize the motor operating relay. The change in contact position removes the motor armature from the supply mains and applies dynamic braking to quickly stop the motor. At the same time, the solenoid is de-energized. Usually the dynamometer is not quite balanced on the first attempt, but takes an extra

COMLETE DIAGRAM OF TORQUE MECH. CONTROL

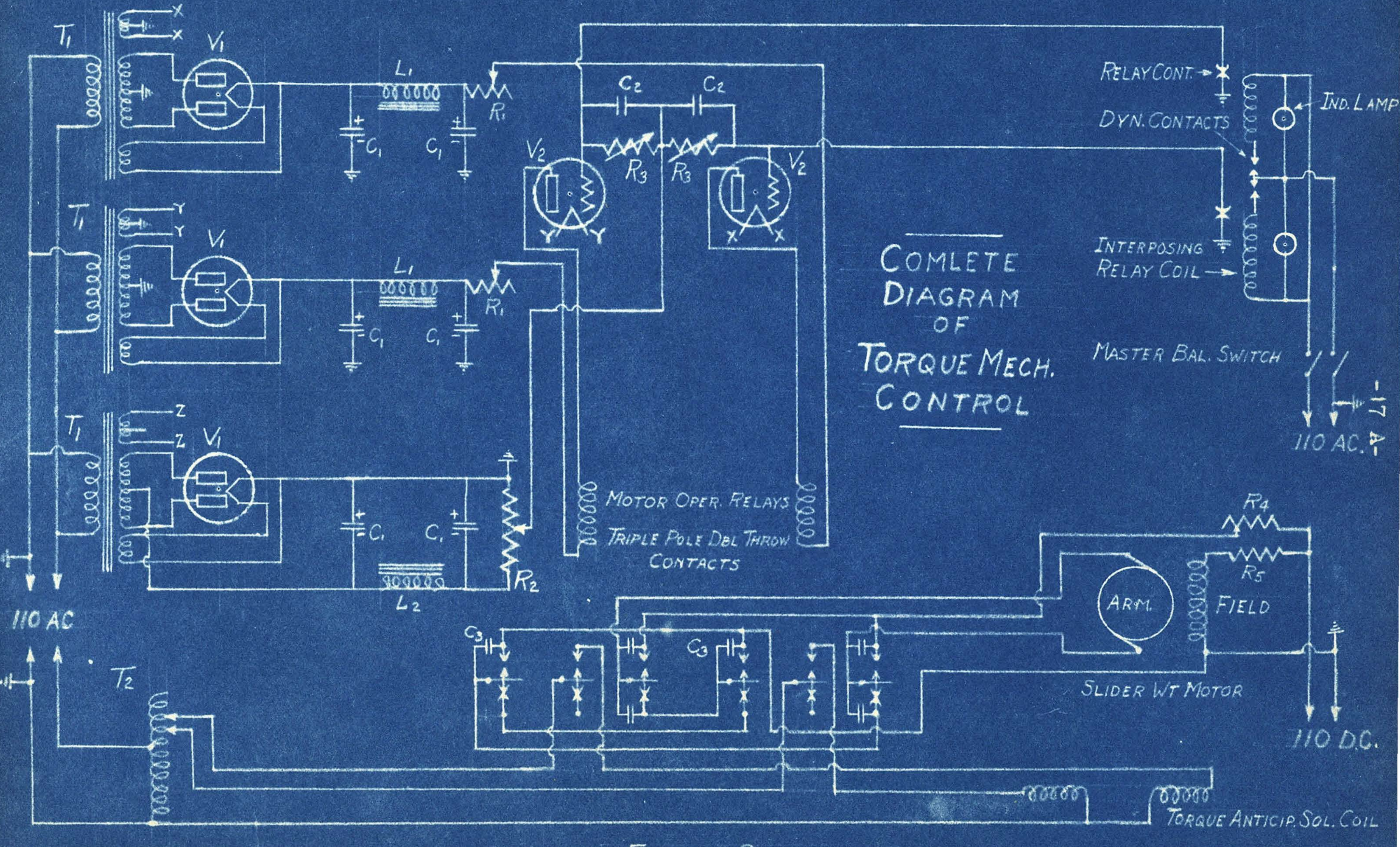


FIGURE 9

NOMENCLATURE OF APPARATUS

SHOWN IN DIAGRAM OF FIGURE 9.

T-1	Radio power transformer - 115 volt primary to 660 volt 50 ma. center tapped; 5 volt, 2 ampere; and 2.5 volt, 4 ampere secondaries.
T-2	Tapped auto-transformer - 115 volt to 30, 40, 50, 60, 70, 80, 90, 100, 110, 120 and 130 volts; 2 amperes 30 to 80 volts, 4 amperes 80 to 130 volts.
V-1	Type 80 radio tube.
V-2	Type 45 radio tube.
L-1	Filter choke - 20 henries at 85 ma.
L-2	Filter choke - 30 henries at 20 ma.
C-1	Electrolytic filter condensers - 600 volt peak, 4 mfd.
C-2	Paper condensers - 600 volt peak, 4 mfd.
C-3	Tubular paper condensers - 600 volt peak, 0.5 mfd.
R-1	Current adjusting resistor - 5000 ohm, 25 watt.
R-2	Voltage adjusting resistor - 25,000 ohm, 25 watt.
R-3	Delay adjusting resistor - 5 megohms total, divided into 0.5 megohm steps connected to a 10 point switch.
R-4	Armature current adjusting resistor - approximately 200 ohms, 200 watts.
R-5	Field current adjusting resistor - approximately 100 ohms, 200 watts.
	Interposing Relay-Contacts closed when de-energized; 115 volt A.C., 50 ma. operating coil (Mfg. by Leach Relay Co.)
	Motor Operating Relay, Triple-pole, double-throw contacts; 115 volt, A.C., 50 ma. operating coil (Mfg. by Leach Relay Co.)

Solenoids - G.E.Typs CR 9503-207-E.

couple of "kicks" to bring it to balance. Unless the slide weight has a long distance to cover, the balancing operation usually takes about a half minute to accomplish.

Examination of Figure 9 shows three separate D.C. power supplies, two of which are associated with the relay coil and vacuum tube (V-2) plate circuits, and the third supplies grid bias voltage for the system. The reason for the separate plate supplies is that due to the characteristics of the equipment used, good regulation was necessary to secure consistant delay characteristics; with poor regulation, a change of conditions in one tube circuit affected the operation of the other tube circuit. To secure good regulation with a single power supply would cost considerably more than the two inexpensive supplies used, and the single supply would probably not have been entirely free of regulation difficulties. The 110 volt direct current supply in the laboratory would have been ideal if 140 to 150 volts were available; the drop in the tubes alone in this service is of the order of 120 volts.

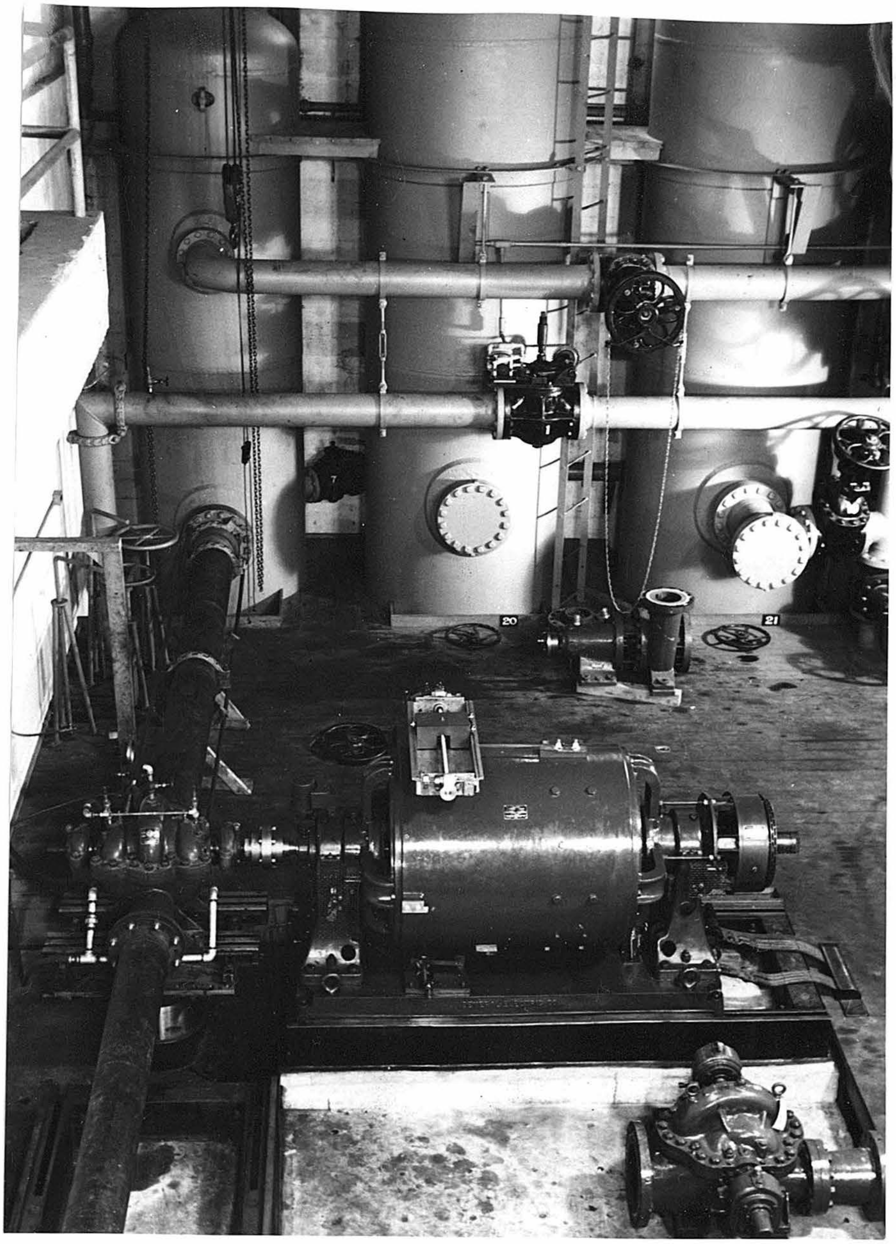
At the time the author became a member of the laboratory staff, considerable difficulty was encountered due to the burning of contacts of the moros motor operating relays. Examination showed that the contacts were interrupting a direct-current inductive circuit. The addition of the six condensers shown as C-3 on

Figure 9 solved this phase of the problem.

In the event the solenoid armatures should rub, undesirable friction would ensue. To protect against this two neon bulbs are connected to ground through the solenoids which are insulated from the dynamometer. Rubbing closes the ground circuit through the solenoid armatures which are fastened to the dynamometer and so are grounded. This device is not illustrated due to its simplicity.

Photographs of the dynamometer, the delay mechanism, pressure gauges, etc., are included in the appendix immediately following.

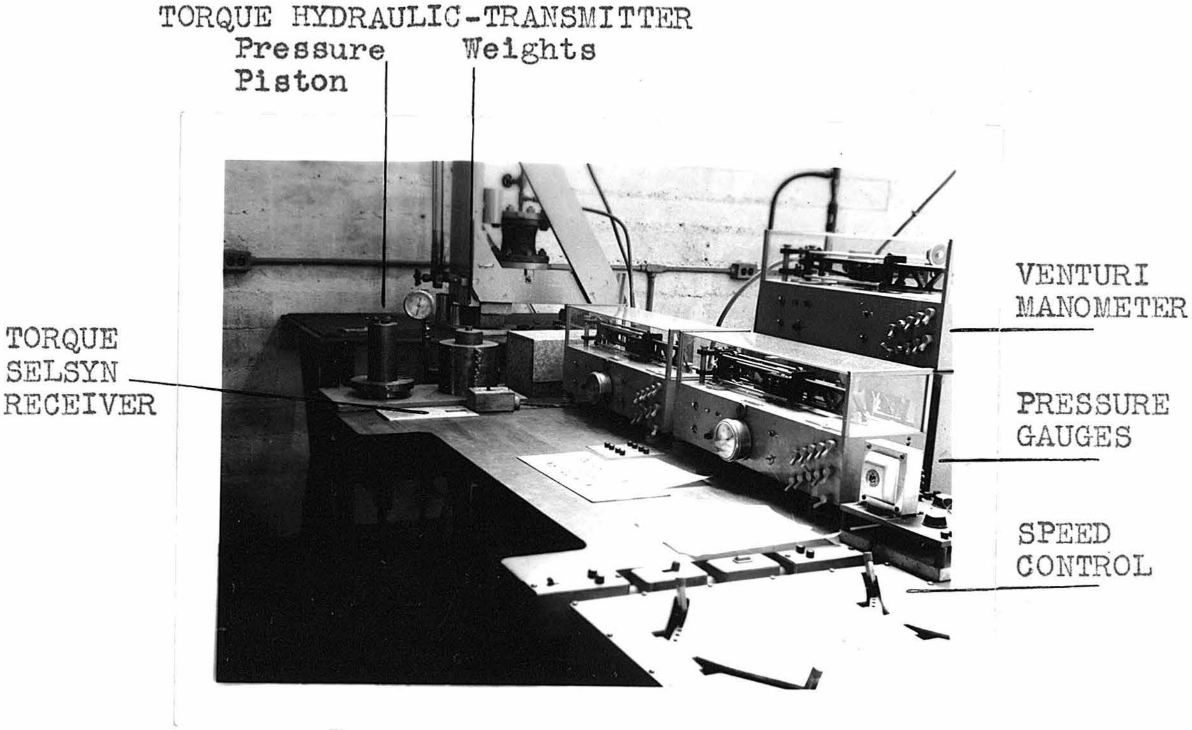
APPENDIX



VIEW OF PART OF LABORATORY SHOWING DYNAMOMETER COUPLED TO A DOUBLE SUCTION PUMP

Picture Taken Prior to Perfection of

Automatic Torque Control



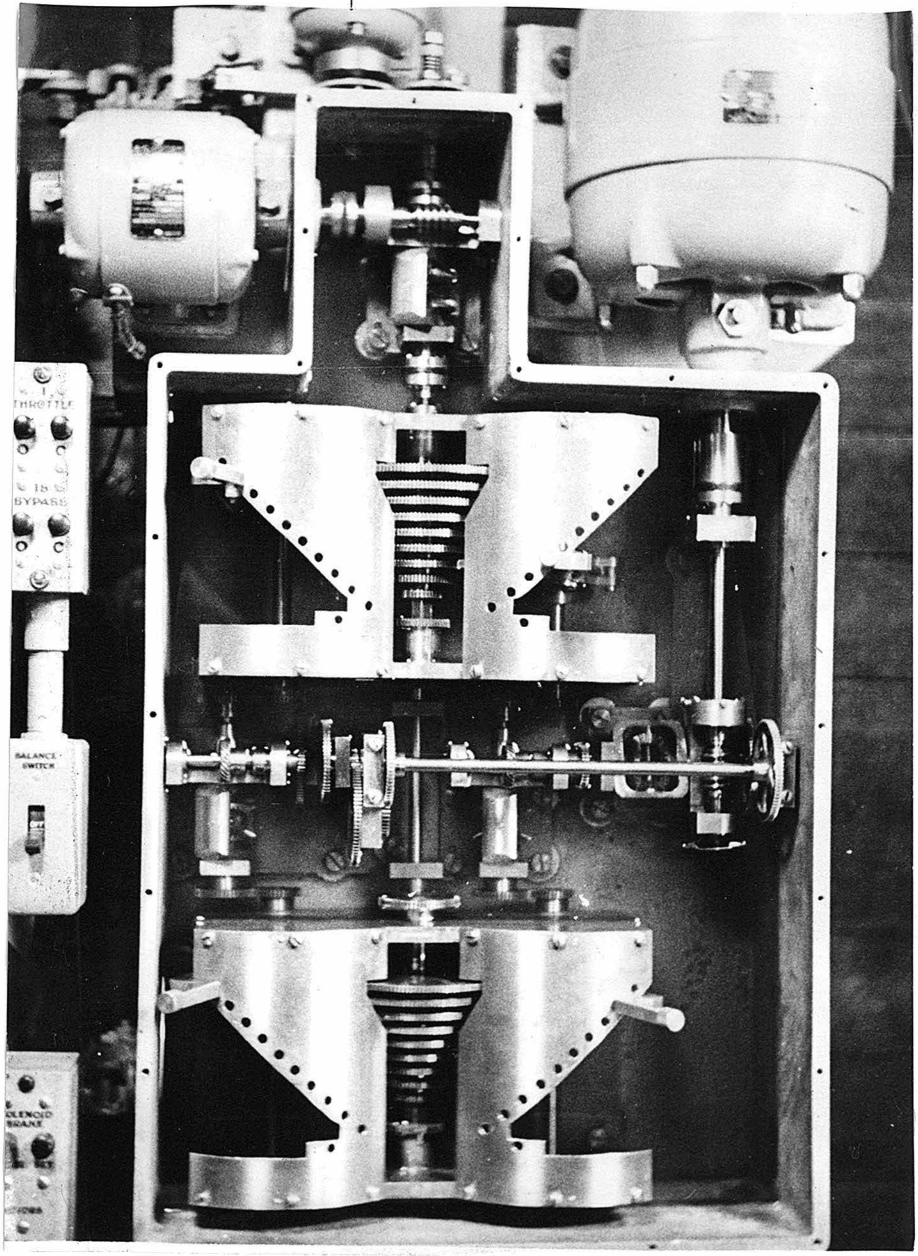
OPERATING AND CONTROL DESK

DYNAMOMETER FIELD
CURRENT CONTROL

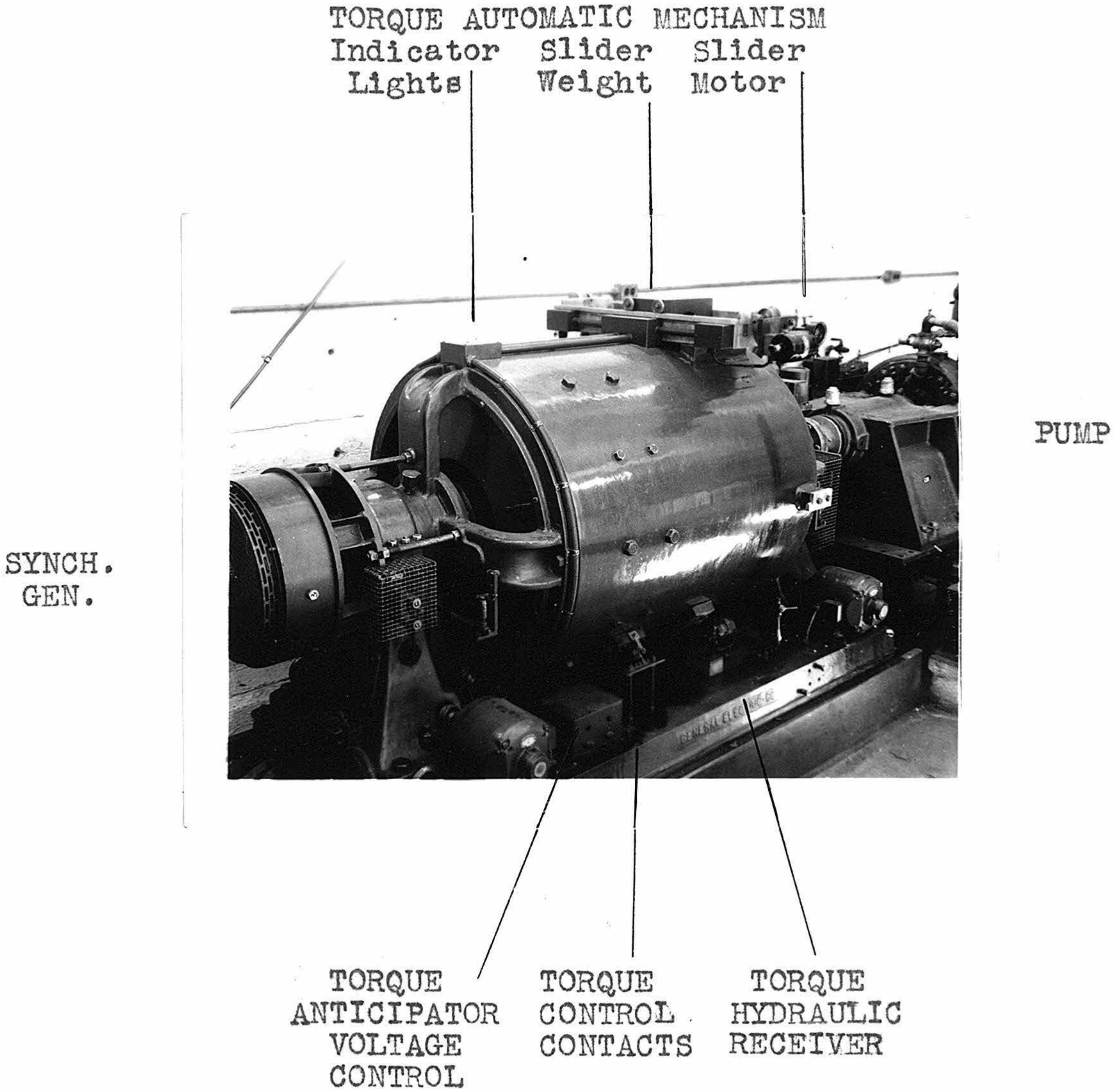
DYNAMOM.
CONTR'LD
MOTOR

CONSTANT
SPEED
MOTOR

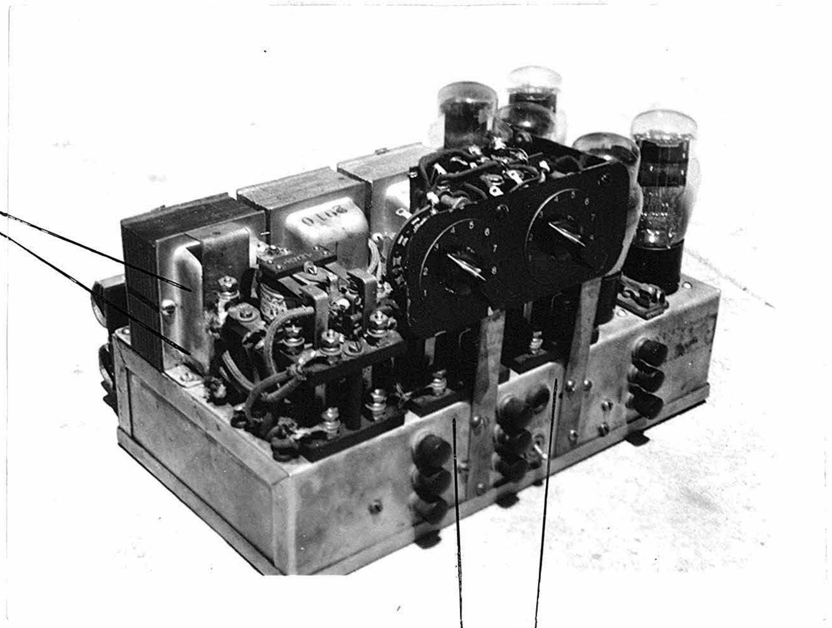
MASTER
BALANCE
SWITCH
ON EDGE
CONTROL
DESK



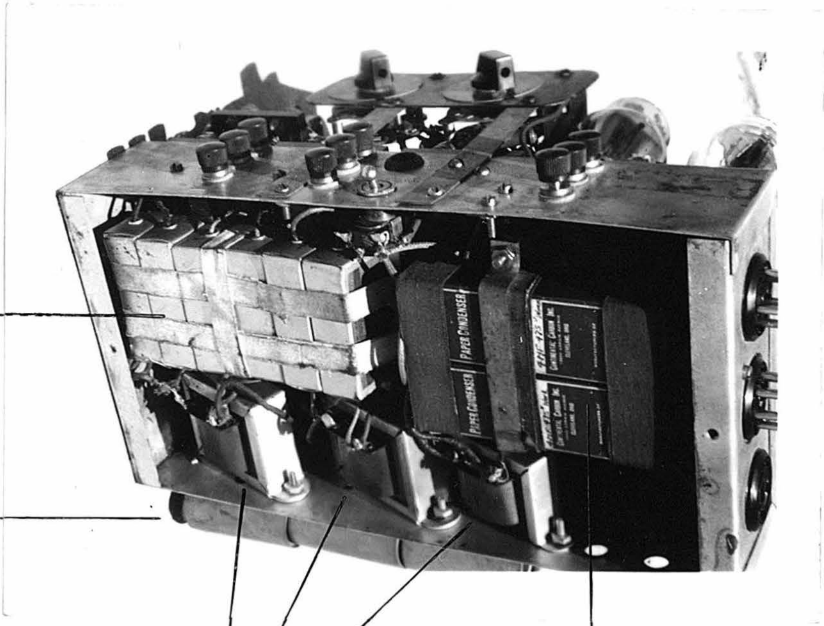
INTERIOR VIEW OF SPEED CONTROL UNIT



DYNAMOMETER



TORQUE MECHANISM CONTROL (FRONT VIEW)



TORQUE MECHANISM CONTROL (BOTTOM VIEW)