AN ELECTRONIC DYNAMOMETER

By

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PREFACE

A need for a dynamometer for measuring the output of motors rated below ten ounce inches of torque has been felt in the field of engineering for a number of years. By taking advantage of the frictionless property of light beams, the electronic dynamometer described in this thesis has been completed and proved by test to be satisfactory for this purpose. With the modifications and improvements which are discussed herein, it is believed that this instrument will be a valuable asset in any laboratory which contains small motors.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation for the valuable suggestions offered by Professor J. R. Norton, Division of Engineering Research and Experiment Station of the Oklahoma Institute of Technology. Invaluable aid was also given by Mr. G. G. Smith of the Engineering Research and Development Laboratory in the actual construction of the instrument. Special thanks are due to Professor A. L. Betts and Professor H. T. Fristoe under whose supervision the work was done and without whose help the project could not have been completed.

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CHAPTER I

INTRODUCTION

Since precision instruments have come into common usage, small motors have become more widely used. Much guesswork has been involved in the choice of a motor for a specific use, and errors in guesses have been costly in many instances. With larger machines more accurate predictions can be made of performance and a motor can be chosen to fit any specified job with a minimum of added cost. In attempting to make measurements of the performance of small motors it has been found that often the friction involved in the measuring instruments overloaded the motor to such a degree as to make accuracy impossible.

A letter was written on March 30, 1950, to the National Bureau of Standards, Washington, D. C., by Professor J. R. Norton, Division of Engineering Research of the Oklahoma Institute of Technology to get the speed-torque characteristics on a Western Electric D. C. motor, KS-5603, 28 volt, 0.6 ampere. On April 11, 1950, Mr. H. K. Cummings, Physicist, Engines and Lubrication Section, National Bureau of Standards, replied, "We have no dynamometer which would be suitable for determining with any accuracy the speed-torque characteristics of a 28 volt, 0.6 ampere DC motor." The electronic dynamometer described in this thesis was tested with the motor mentioned above, and the speed-torque curves are included in the data. Because of the electronic nature of the measuring techniques friction is small so that a minimum of error is present in the results.

CHAPTER II

SPEED MEASUREMENT

Principles of Operation

In the development of the electronic dynamometer several methods were discussed for measuring the speed of the test motor. The basic trouble with most methods was the load placed on the motor by the measuring equipment. Many of the small motors do not have enough torque to operate an ordinary tachometer. The method finally used (See Figure 1) employed a polished steel disk, with a small hole in its periphery, coupled directly to the motor shaft. A small lamp was placed in a position where the hole in the disk would pass it each time the motor turned through 360 degrees. Opposite the light bulb, on the other side of the disk, a photocell was mounted. Each time the disk made one complete revolution a pulse of light was cast upon the photocell, giving a pulse of current. A direct measurement of this current gave no indication of speed, since the pulse width and amplitude varied inversely with the speed and the number of pulses per unit time varied directly with the speed. Some method had to be divised whereby the number of pulses per unit time could be counted with the pulse width and amplitude not a factor in the measurements. This was accomplished by applying the pulse to an amplifier, which was operated to saturation with the smallest amplitude pulse. This eliminated the amplitude variation but the width variation remained. The signal from the amplifier was then applied to a "one-shot" multivibrator and

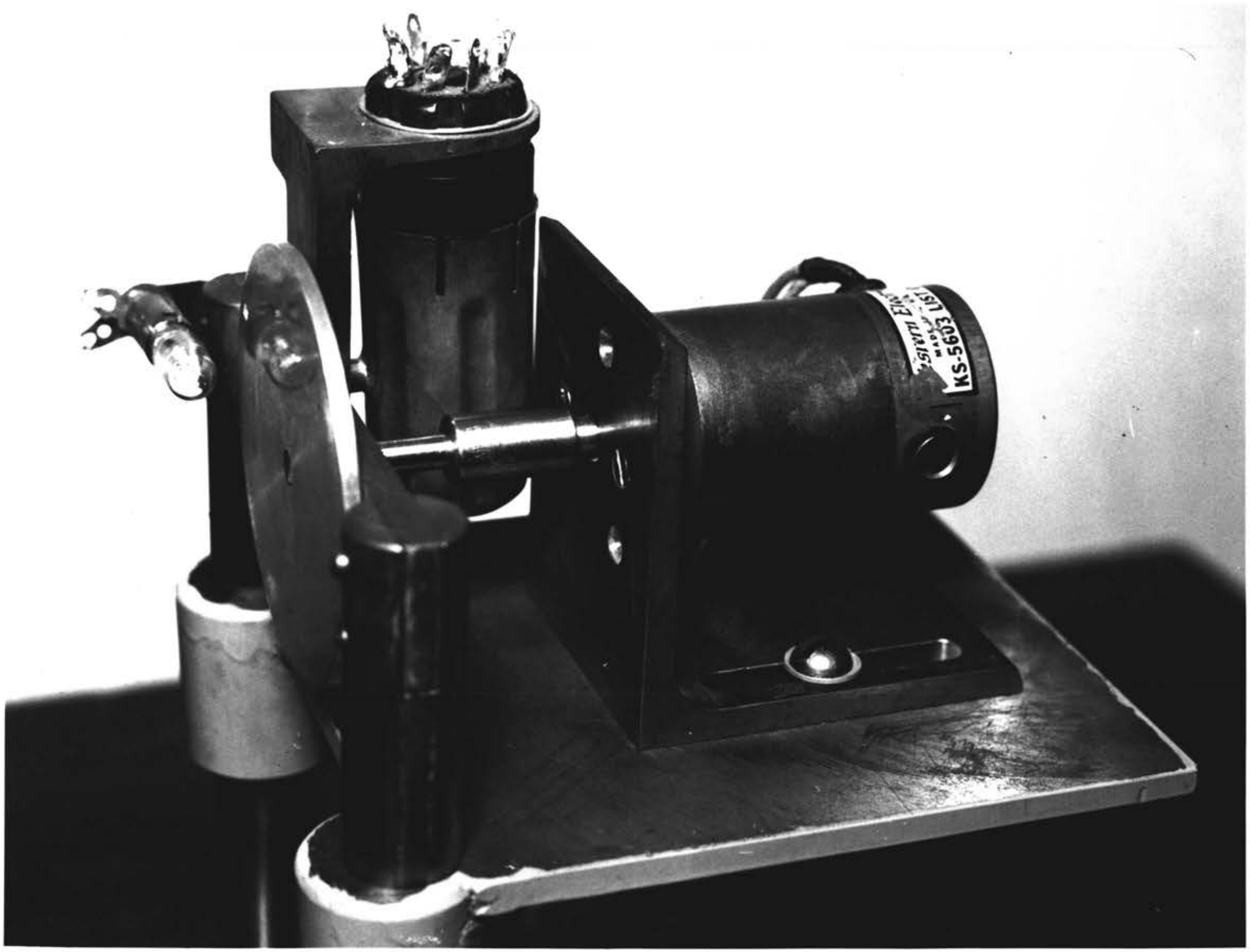


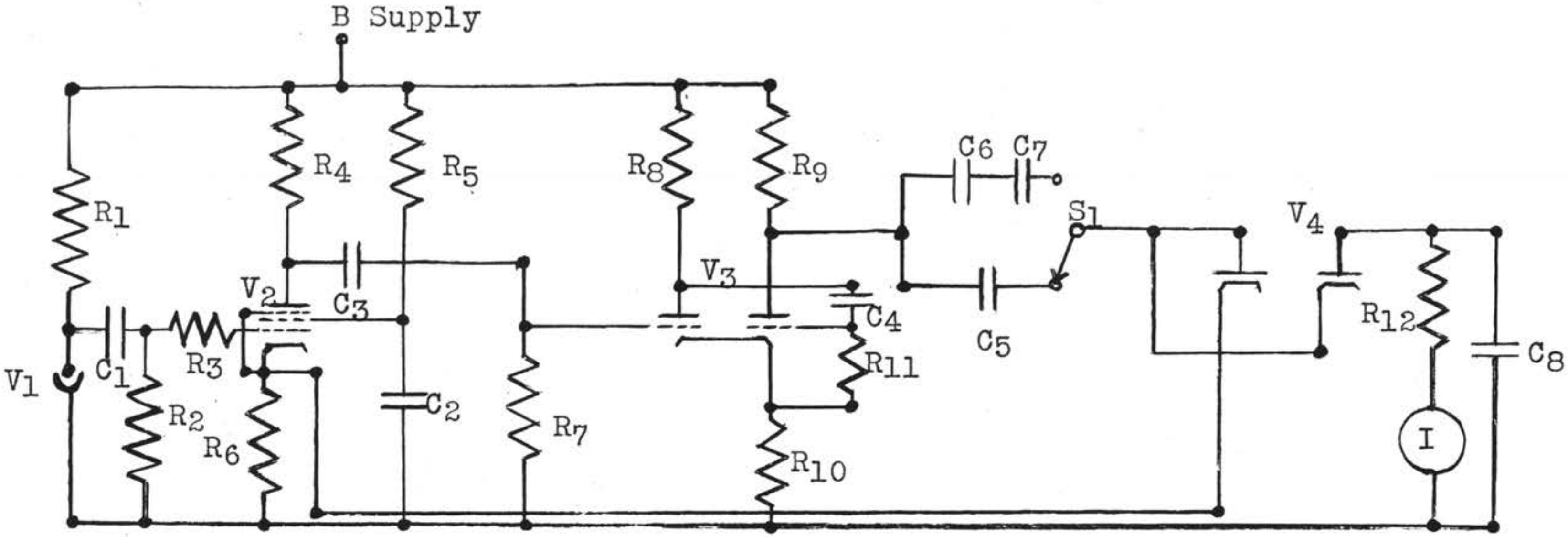
Figure 1. Photograph of the Speed Measurement Section of the Dynamometer

this eliminated the width variation. The output of the multivibrator was then applied to a metering circuit using a twin diode and a fifty micro-ampere meter and the current through this circuit was found to be proportional to the speed of rotation.

Circuit Operation

The circuits used for speed measurement are straightforward with only a few revisions. (See Figure 2.) When the light strikes V1, a RCA 929 photocell, current passes through R1 and a negative pulse is coupled through C1 and R2 to the grid of V2 which is a 6AG5 used as an amplifier. R3 is for isolation purposes. When the grid of V2 goes negative the plate current decreases and the plate potential rises. The self-biasing resistor, R6, is not by-passed introducing negative feedback which will tend to make the output pulse amplitude independent of the input pulse amplitude.

The positive pulse from the plate of V2 is coupled through C3 and R7 to the grid of the left side of V3. The variable cathode resistor, R10, is adjusted so that with no pulse input the left side of V3 is cut off. Since the grid of the righthand side is connected to the cathode through a resistor, R11, the righthand side normally is conducting. When a positive pulse is applied to the grid on the lefthand side of the tube that side conducts and its plate voltage drops. This drop in voltage will instantaneously appear across R11, cutting off the flow of current in the righthand side of V3. The width of the pulse is



PARTS LIST

R_1 - 5 Megohms
R_2 - 0.5 Megohms
R_3 - 4.7 K ohms
R_4 - 50 K ohms
R_5 - 50 K ohms
R_6 - 200 ohms
R_7 - 0.5 Megohms
R_8 - 18 K ohms
R_9 - 18 K ohms
R_{10} - 0 - 3000 ohms
R_{11} - 0.5 Megohms
R_{12} - 1.0 Megohms

C_1 - 0.05 mfd
C_2 - 16 mfd
C_3 - 0.005 mfd
C_4 - 0.1 mfd
C_5 - 0.011 mfd
C_6 - 0.009 mfd
C_7 - 0.01 mfd
C_8 - 1.0 mfd

V_1 - RCA 929
V_2 - 6AG5
V_3 - 6J6
V_4 - 6AL5

B Supply is 250 volts

Figure 2. Circuit Diagram for Speed Measurement.

small, since it is determined by the length of time required for the hole in the disk to pass the lamp, and this condition will exist only momentarily. The circuit of V3 will then return to its normal condition and remain there until the next pulse is applied to the circuit. Thus the plate voltage of the right-hand side of V3 will rise and then drop and this pulse may be coupled to a metering circuit.

In the design of this multivibrator care must be taken to insure the right value for time constants throughout the circuit. The dynamometer was to cover a range of a few revolutions per minute to an approximate top range of 40,000 revolutions per minute. The disk used for measuring speed had a one and one-half inch radius, and the hole through which the light passed was of a one-eighth inch diameter. These dimensions made the hole stay in front of the lamp for approximately one-eightieth of the time required for a revolution. The time constants of R7 C3 and R11 C4 had to be such that the circuit would be certain to be triggered on each pulse and would not be triggered more than once per pulse. Thus the time constants had to be long in respect to the pulse width when the test motor was turning at a low speed, yet short with respect to the frequency of repetition of pulses at the higher speeds of the motor.

The coupling arrangement of C5 or C6 and C7 was chosen to give full scale deflection on the fifty micro-ampere meter used in the metering circuit for two different speed ranges which were calibrated with the test motor. The no-load speed of the test motor, when rated voltage was applied was approximately 6800 revolutions per minute, so only two ranges, 0 - 3000, and 0 - 6000 revolutions per minute, were calibrated on the test model. The calibration curves for these two ranges are shown in Figures 3 and 4. These ranges were calibrated by the use of an electronic switch and comparison of the frequency of the pulses with the output of an audio oscillator as shown in Figure 5. The sizes of the coupling capacitors from the multivibrator to the metering circuit were chosen by the direct trial method of setting the rotation rate of the motor at the value required for maximum range reading and varying the coupling capacitor until full scale deflection occurred. For the 0 - 3000 revolutions per minute range this coupling capacitor was found to be .011 microfarads, and was found to be .00474 microfarads for the 0 - 6000 revolutions per minute range. This latter value was made up of a .009 and a .01 microfarad condenser in series.

With these values of coupling capacitors data was taken for plotting Figures 3 and 4, and this data appears below.

DATA FOR 0 - 3000 RPM RANGE

Speed		Meter Reading
rpm	cps	micro-amperes
3000	50.0	50.0
2490	41.5	45.4
1980	33.0	40.0
1590	26.5	35.0
1242	20.7	30.0
897	14.95	23.5

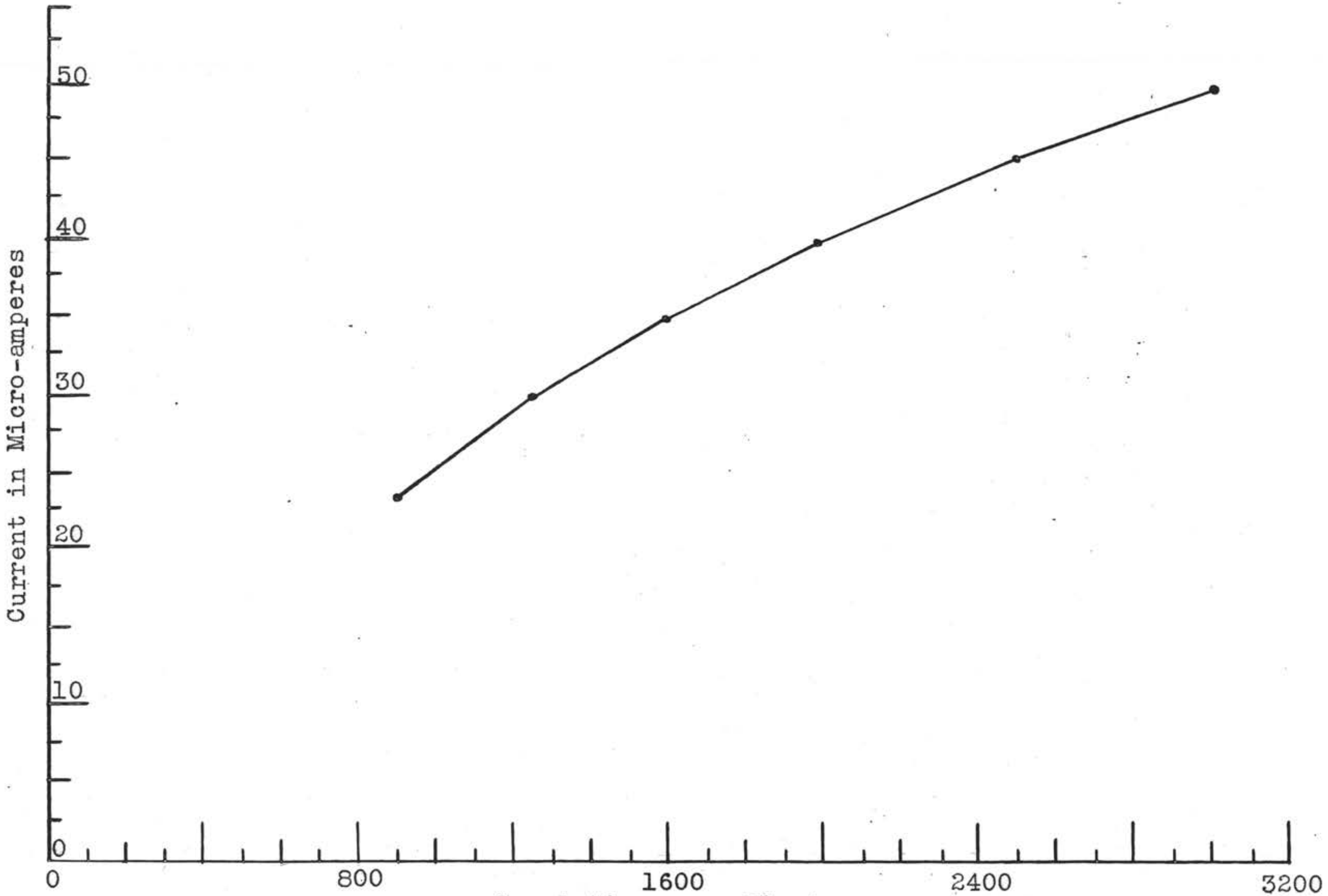


Figure 3. Speed Calibration for 0 - 3000 rpm Range.

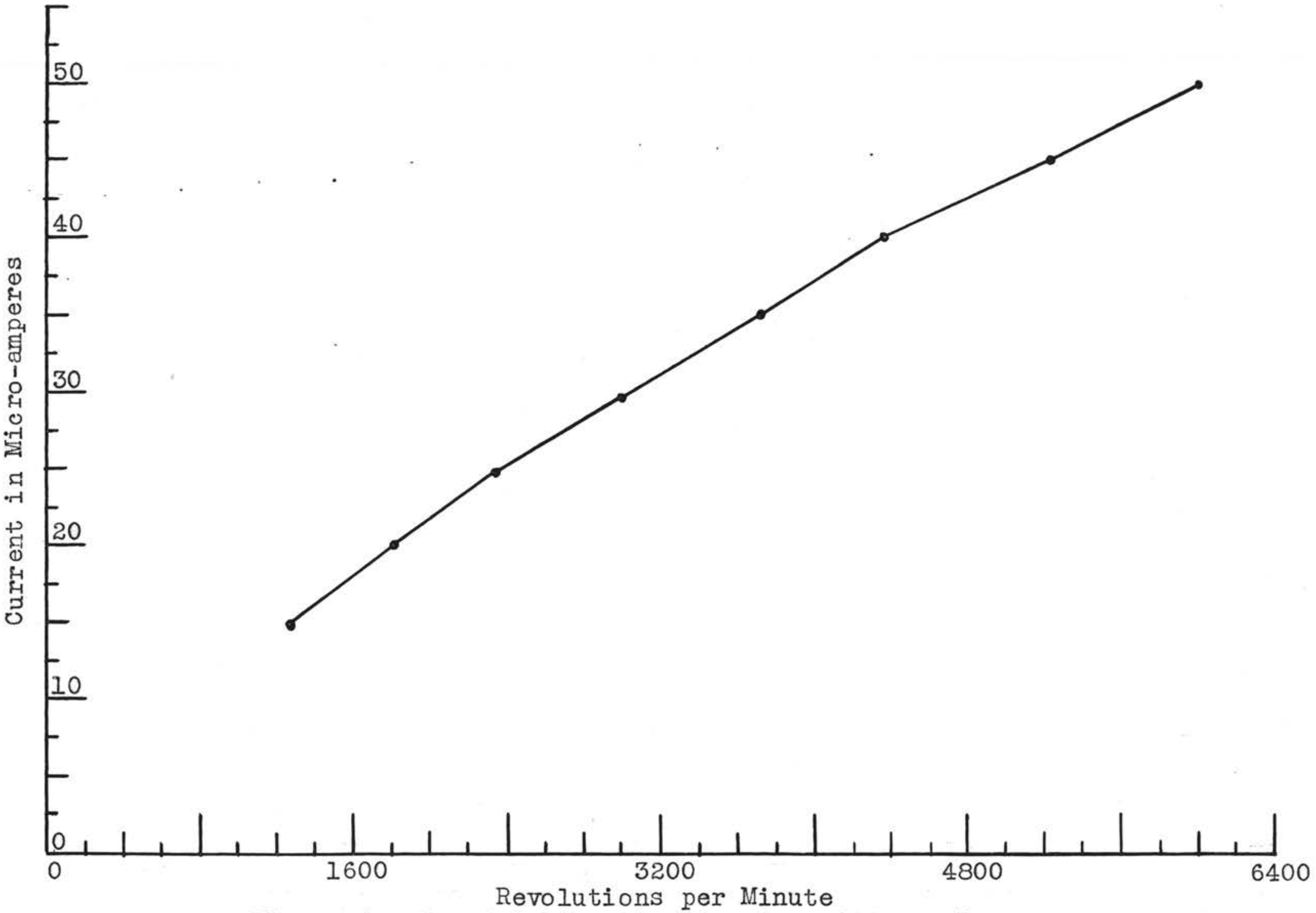


Figure 4. Speed Calibration for 0 - 6000 rpm Range.

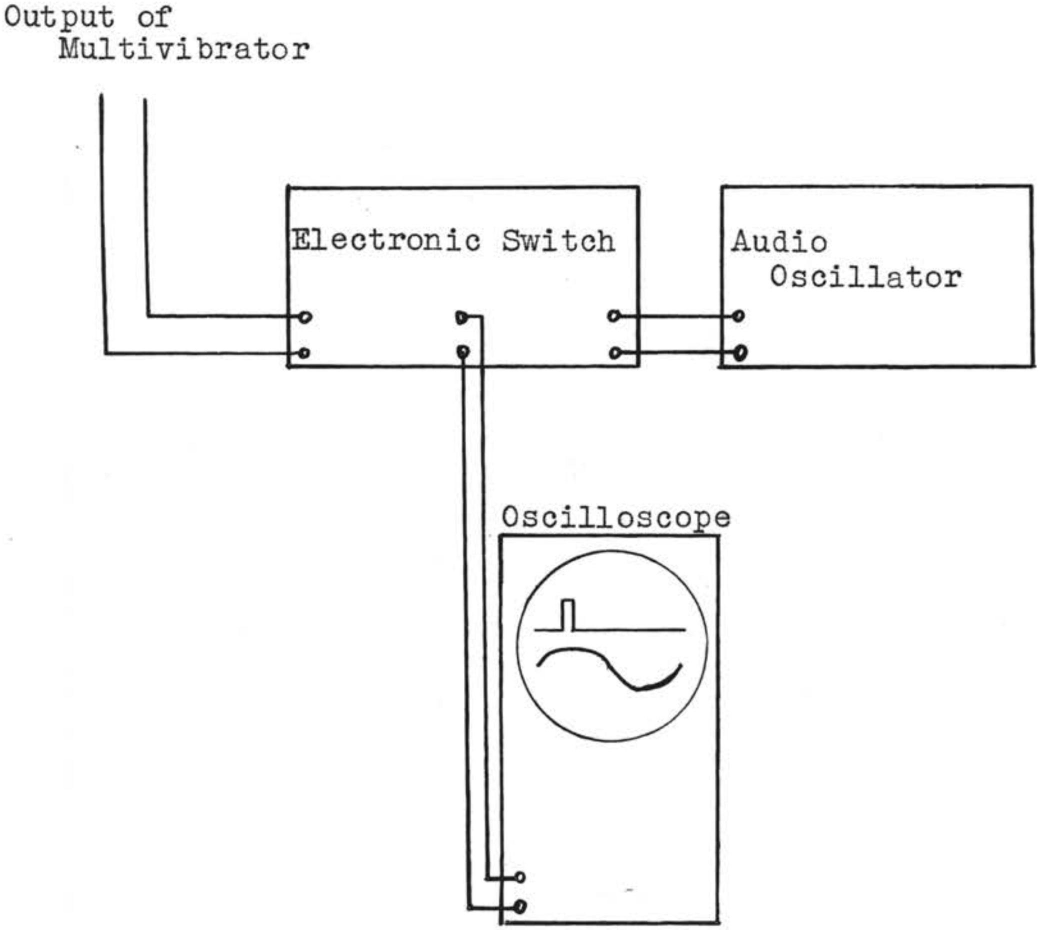


Figure 5. Connections For Speed Calibration

DATA FOR 0 - 6000 RPM RANGE

Speed rpm	 cps	Meter Reading micro-amperes
6000	100.0	50.0
5220	87.0	45.0
4380	73.0	40.0
3720	62.0	35.0
3000	50.0	29.9
2352	39.2	24.9
1836	30.6	20.0
1278	21.3	15.0

The metering circuit consists of V4, R12, C8, and the micro-ammeter. It is a circuit which uses a dual diode 6AL5 with a slight positive potential applied to the cathode of the lefthand section in order that no current will flow if no pulse is received. This positive potential was obtained by connecting the cathode of the left section of V4 to the cathode of V2. The slight variation of the cathode potential of V2 due to the current feedback mentioned before had no harmful effects upon the metering circuit and was included in the calibration curves shown in Figures 3 and 4.

In explaining the action of the diode integrator, assume steady state conditions of voltage on the plate of the righthand side of V4. When a positive pulse was applied to the coupling capacitor it charged very quickly to a new value through the low impedance of the lefthand section of V4. As the positive pulse decreased this coupling condenser discharged through the right-hand section of V4 until the charge reached a minimum value. As the positive pulse recurrs the action will repeat itself and the average current through R12 and the meter will be proportional to the input frequency. The only apparent limitation on the circuit is the time constant of the coupling condenser and the resistor R12. For a linear scale calibration this time constant multiplied by the frequency of operation should be very much smaller than one.[1]

On the two scales calibrated, the meter readings were not found to be multiples. Because of this the most simple method of determining speed was to use the calibration curves of Figures 3 and 4 with the instrument rather than trying to calibrate the meter directly in revolutions per minute. This difficulty may be corrected by selecting different values for circuit components.

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[1] P. H. Miller, Jr., "Variable Speed Motor and Electric Tachometer," Review of Scientific Instruments, December, 1944, p. 348.

CHAPTER III

TORQUE MEASUREMENT

Principle of Operation

The measurement of torque was much more difficult to accomplish than was the speed measurement. Along with the same difficulties of loading the motor by friction came the author's desire to make all measurements with as few mechanical linkages as possible. When mechanical means of measurement are used the accuracy of data not only depends upon the reading of the instrument by the user but also is effected by climatic conditions. For these reasons a method was devised using no mechanical coupling to the test motor. (See Figure 6). Electromagnets were mounted on a polished aluminum disk and this was fastened to a shaft. The shaft was mounted on two bearings and another disk mounted on the other end. Between the two bearings a rod was attached to the shaft and weights of one, two, four, and eight ounces were made to be attached to this rod. The entire mounting of these disks was made movable so that it could be moved with respect to the polished steel disk used in speed measurements. By this method a load could be placed on the motor and the entire load measured with no difficulties or inaccuracies due to mechanical coupling. The amount of the load could be varied both by changing the position of the disks or by changing the amount of current flowing in the electromagnets.

When current was passed through the electromagnets the field surrounding them caused eddy currents to flow in the disk coupled

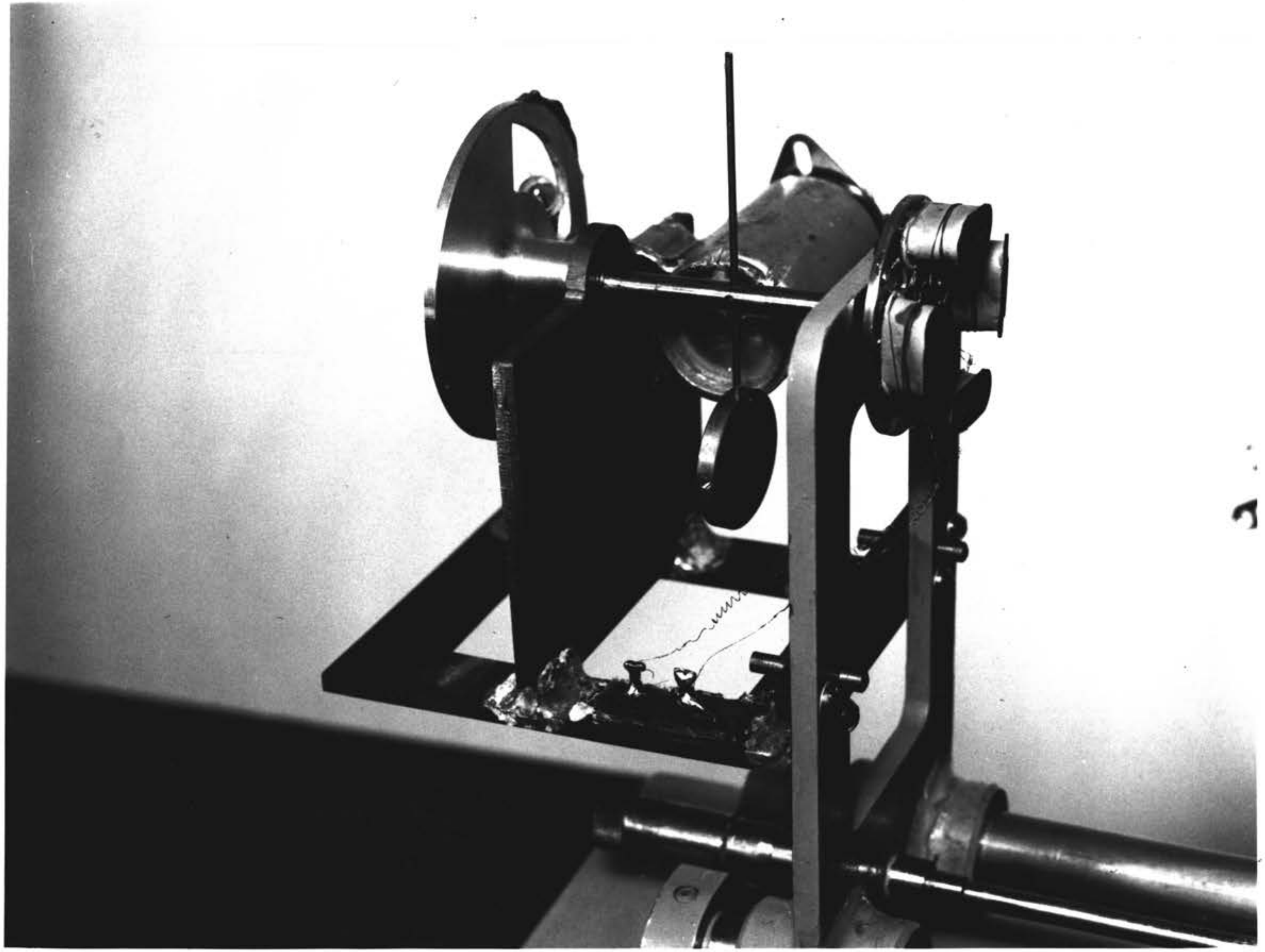

Figure 6. Photograph of the Torque Measurement Section of the Dynamometer

to the motor for speed measurements. This tended to make the disk on which the electromagnets were mounted rotate. With the weight placed on the rod mentioned before, the disk with the magnets could rotate only through an angle proportional to the torque output of the motor. The torque required to move the weight through an angle was equal to force times distance and in this case was equal to the weight times the moment arm times the sine of the angle through which the disk turned. Since the instrument was intended for use with very small motors the moment arm was made one and one-half inches long with the weights one, two, four, and eight ounces, as mentioned previously. The only change necessary to change ranges was to change the weight.

The problem remaining was then to find some method by which the angle of turn could be measured. The weight and moment arm for any given scale were constants so the angle of turn was the only variable. The disk on the opposite end of the shaft from the disk with the magnets was for this purpose. A slot whose width increased in magnitude approximately as the sine of the angle through which the disk turned was cut in this disk. More care was taken with the slot at angles below forty-five degrees because that would be the more useful range of the instrument. A lamp was then mounted on one side of the disk, and a photocell on the other side, as shown in Figure 6. As the disk was turned the amount of light falling upon the photocell increased and thus the current from the photocell increased, with this increase proportional to the torque output of the test motor.

For the calibration curve shown in Figure 8 the angle of

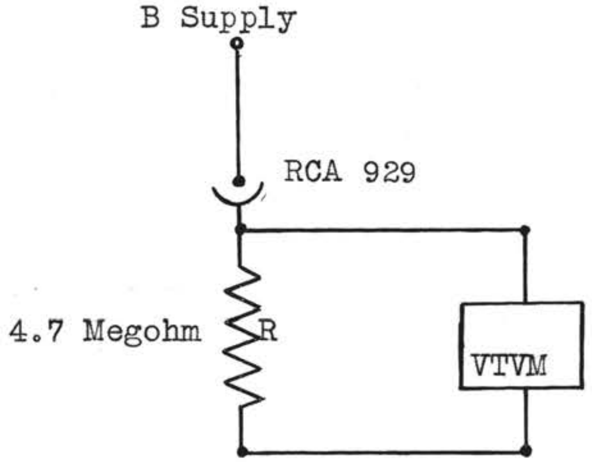

Figure 7. Circuit For Torque Measurement

turn of the disk was used as a reference and the voltage caused by the current flow in the photocell was read across the resistor as shown in Figure 7. For test purposes a D.C. vacuum tube voltmeter was used for making this measurement but in the final model this voltmeter would be built into the instrument so that no auxiliary equipment would be necessary. The data for Figure 8 is shown below:

Data for Figure 8

Angle in degrees	Voltage	Torque in ounce-inches
1	0.15	0.026175
2	0.26	0.052350
3	0.75	0.078510
4	1.20	0.104640
5	2.04	0.130740
6	2.79	0.156795
7	3.60	0.182805
8	4.30	0.208755
9	5.00	0.234645
10	5.60	0.260475
15	7.80	0.388230
20	8.40	0.513030
25	8.70	0.633930
30	8.80	0.750000
35	8.80	0.860370
40	8.80	0.964185
45	8.80	1.060665

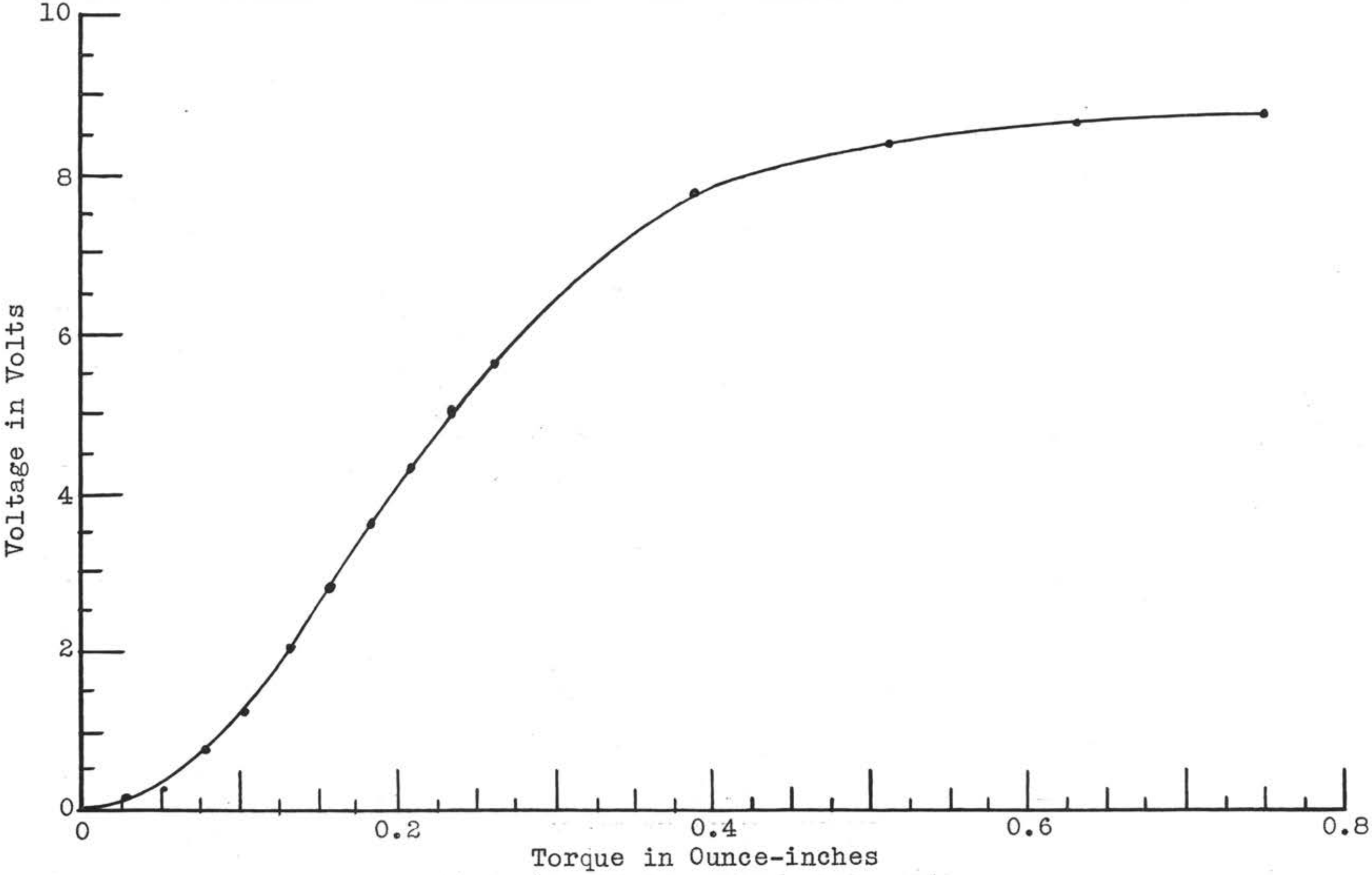

Figure 8. Torque Calibration Curve

For the calibration curve shown in Figure 8, the actual torque was found corresponding to the angle of turn of the disk. This was plotted for the one ounce weight since it is a simple process to multiply the torque shown by either two, four, or eight for the other weights used.

No noticeable change in voltage occurred after the disk had turned through thirty degrees, so the useful range is below that angle of turn. On the final instrument the slot in the disk would be cut more carefully and this useful range could be extended.

The data for figure eight was directly dependent upon the amount of light striking the photocell, so it was a function of the brilliance of the lamp used. For this reason a rheostat was placed in series with this lamp. This made it possible to calibrate the instrument easily and quickly each time it was to be used. All that was necessary to calibrate the instrument was to turn the disk through some known angle and adjust the brilliance of the lamp until the voltage measured in the photocell circuit was equal to the value found in Figure 8 for that angle of turn. In this manner inaccuracies due to mis-calibration were eliminated.

CHAPTER IV

RESULTS

The motor used for test purposes was a Western Electric k-5603, 28 volt, 0.6 ampere, D. C. motor. Difficulty was encountered in making measurements on the motor, not because it was too small, but because it was too large. This was because of the size of the disk upon which the electromagnets were mounted, and because of the limited number of ampere turns used. With the rated voltage applied to the test motor it was not possible to decrease the speed more than a few hundred revolutions per minute by loading it with the torque measuring device. For this reason a lower voltage was applied to the motor so that a wider speed-torque variation could be obtained.

Figure 9 shows the speed-torque characteristics of the test motor with 19 volts applied, and the data for this curve appears below:

Data for Speed-Torque Curve of Figure 9.

Speed rpm	Torque Ounce-inches
4560	0.000
4110	0.105
3855	0.131
3705	0.156
3330	0.183
2100	0.196

It may be noticed from Figure 9 that the speed dropped

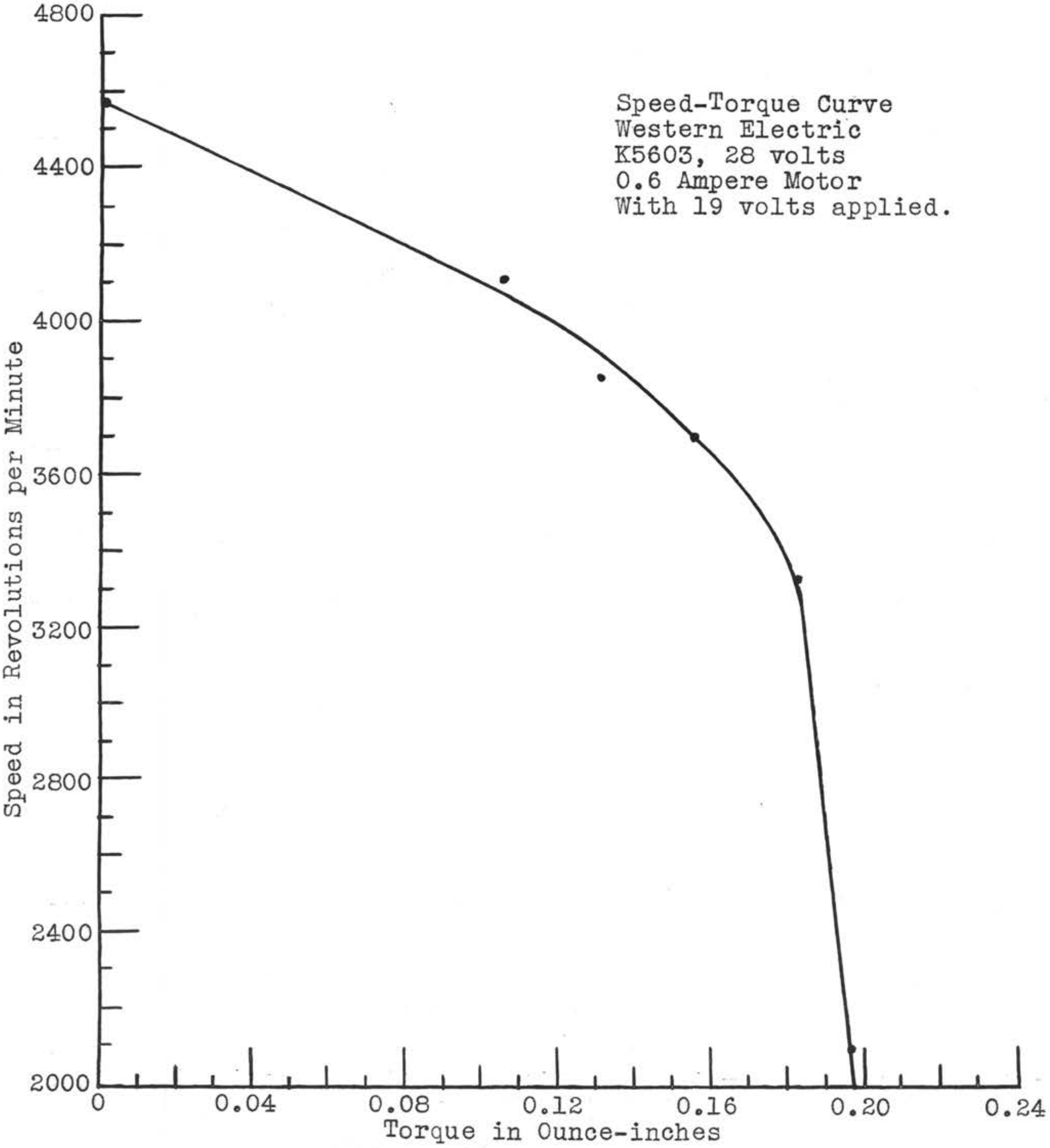

Figure 9. Speed-Torque Curve

off slowly from no-load conditions to approximately 0.17 ounce-inches of load. After this the speed dropped rapidly with very little additional load applied. If this were the speed-torque characteristic of the motor at rated voltage, full load would be approximately 0.16 ounce-inches, at 3660 revolutions per minute, which is an output of 1/1725 horsepower.

Because of the low output with 19 volts applied to the test motor, the voltage was increased to 22 volts so that the increased output might be noted. Figure 10 shows the speed-torque curve for the motor with 22 volts applied, and the data for this curve is shown below:

Data for Speed-Torque Curve of Figure 10

Speed rpm	Torque Ounce-inches
6000	0.000
5730	0.156
5730	0.196
5412	0.260
5250	0.388
5040	0.488
4950	0.513

With the torque measuring device that was in use on the test model a load large enough to show the drop in speed as was seen in Figure 9 was not possible under the increased voltage conditions. However the approximate curve for this is shown as a dotted line on Figure 10. From this the approximate rated load with 22 volts applied would be 0.5 ounce-inches at 5000 revo-

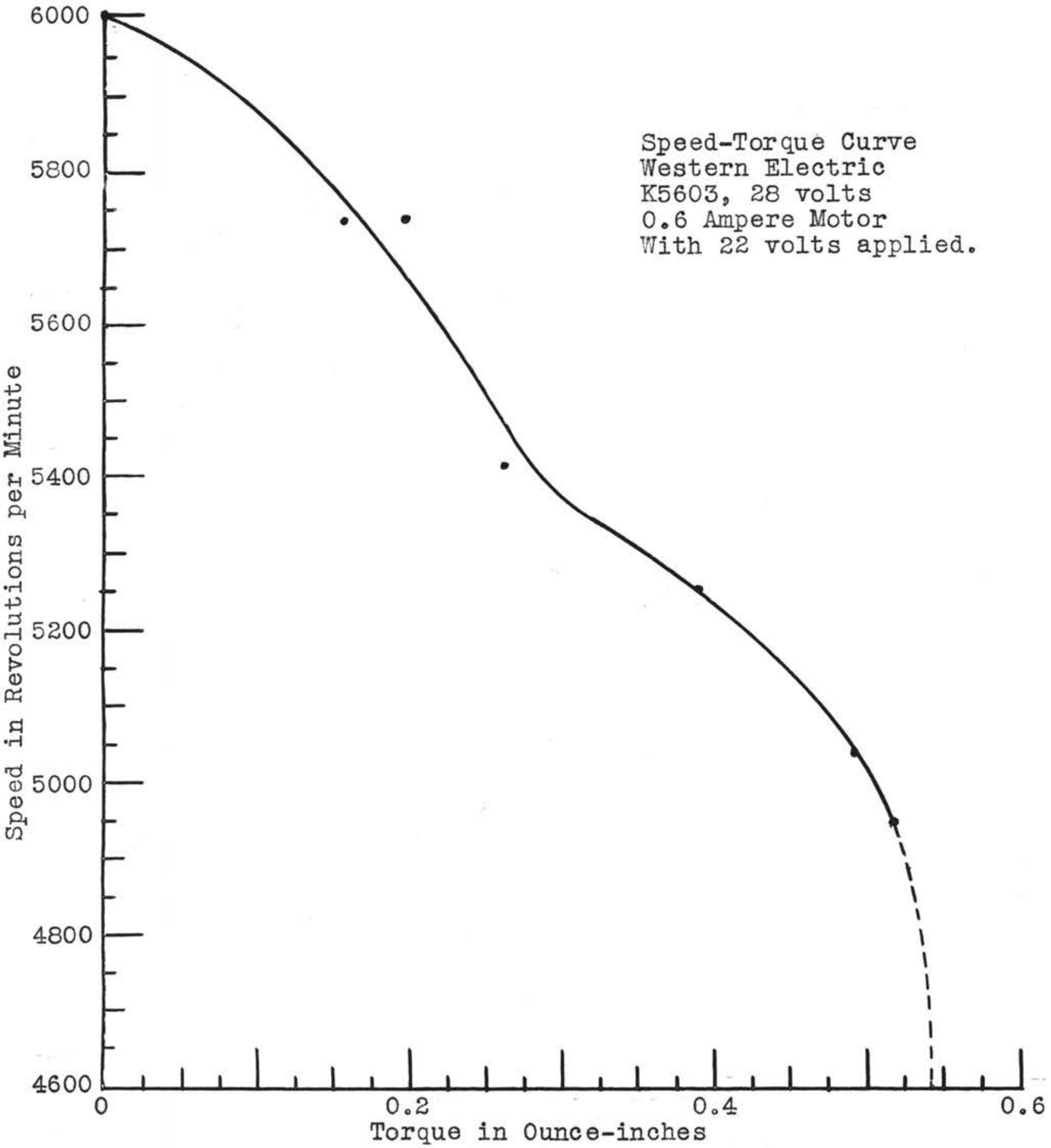

Figure 10. Speed-Torque Curve

lutions per minute, corresponding to an output of 1/400 horsepower. Thus by increasing the voltage by only three volts the output was changed from 1/1725 to 1/400 horsepower.

Since the change in output was so great for the two voltages already shown, it was decided to apply rated voltage to the motor and check the output. Figure 11 shows the speed-torque curve for the test motor at its rated voltage of 28 volts, and the data for this curve is shown below.

Data for Speed-Torque Curve of Figure 11

Speed rpm	Torque Ounce-inches
6780	0.000
6600	0.183
6480	0.260
6300	0.388
6240	0.513

As may be seen from the curve, when rated voltage was applied the speed of the motor at no-load was 6780 revolutions per minute. This was above the range of the speed scales, so the speeds were checked directly by using an audio oscillator in the same manner as the speed scales were originally calibrated. The load applied to the motor was only capable of slowing the speed to 6240 revolutions per minute. This did not show the drop in speed as was shown in Figure 9, so as in Figure 10, a dotted line was drawn in Figure 11 to approximate the rated load of the motor. This was found to be 0.7 ounce-inches at 6200 revolutions

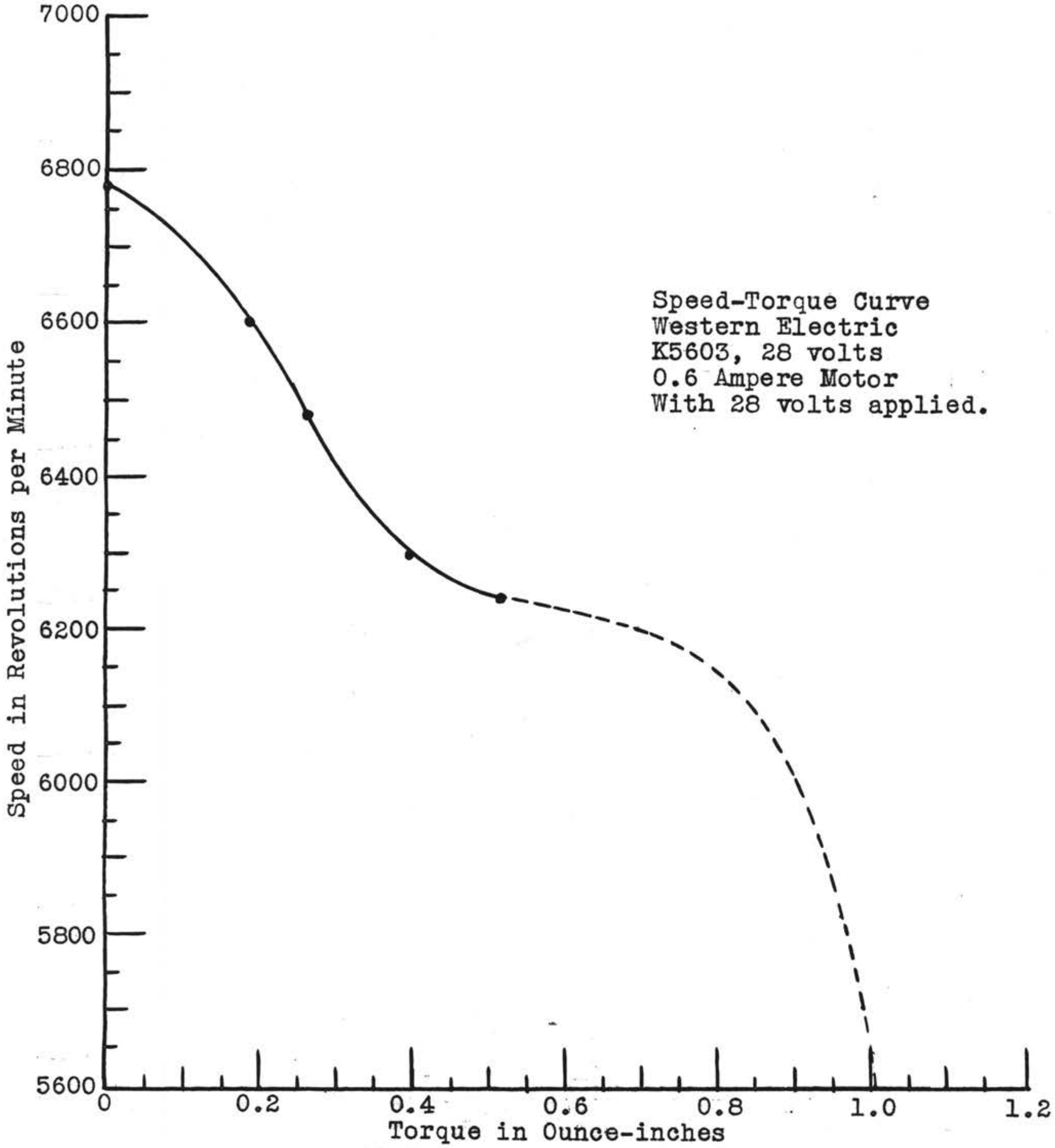

Figure 11. Speed-Torque Curve

per minute, corresponding to an output of 1/232 horsepower. Since this was an approximation it would seem logical that the test motor was rated at 1/250 horsepower.

Even though the speed-torque curves shown for the test motor did not give a complete picture of the capabilities of this motor, they were sufficient to prove that the electronic dynamometer is a success. With various revisions which will be discussed in Chapter V, this instrument could be designed to measure the output of motors from almost infinitesimal outputs to outputs of a horsepower or more.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The goal of this project was to design and construct an electronic dynamometer capable of measuring the output of very small motors. The dynamometer described herein fulfills that purpose. Diagrams showing the construction of the various parts were shown, along with complete circuit diagrams and explanations of the operation of each major unit. The simplicity of operational procedure excluded the need for specific operating instructions.

The major cost of the dynamometer is the cost of the skilled labor necessary for the accurate construction required. A cost statement was obtained from the Research and Development Laboratory and the cost of construction was approximately $300.00 for labor and $20.00 for material. The cost of the additional circuit components required should not exceed $30.00 so that the total cost should not exceed $350.00. When constructed on a commercial basis this cost should be reduced by at least ten per cent. However the cost as it is now is not excessive in comparison with other instruments of approximately equal accuracy, and is less than some instruments of much less importance.

Plan of Action

Plans for the immediate future call for the improvement of the dynamometer in several different ways, and the assembling of a final instrument to be subjected to more rigorous tests. It is planned to more accurately determine the usable range of the instrument.

The principle fault of the test model is its inability to load a motor as much as may be desired. Since the load placed on the motor is increased by increasing the radius of action of the electromagnetic force, the first improvement will be to increase the size of the disk upon which the electromagnets are mounted. This will make it possible to increase the radius of action of the magnets. Since the force increase is proportional to the square of the radius increase, it is possible to make the force nine times as great by increasing the radius by a factor of three. When the radius is increased there will be room for additional electromagnets. Since the force exerted is directly proportional to both the number of turns and the amount of current flow, the force may be made four times as great by doubling the number of turns and the current capacity. Another great factor is the material of which the disk is made. As was mentioned before, the disk is now made of aluminum, a non-magnetic material. When the larger disk is made, it will be made of steel so that the major portion of the magnetomotive force drop will be in the air gap between the magnets and the speed disk. In this manner the load placed on the motor may also be increased.

Another improvement to be made is the careful re-design of the slot cut in the disk used for torque measurement. As was shown in Figure 8, the torque may be measured accurately through a turn of only thirty degrees. By reconstruction of the slot the

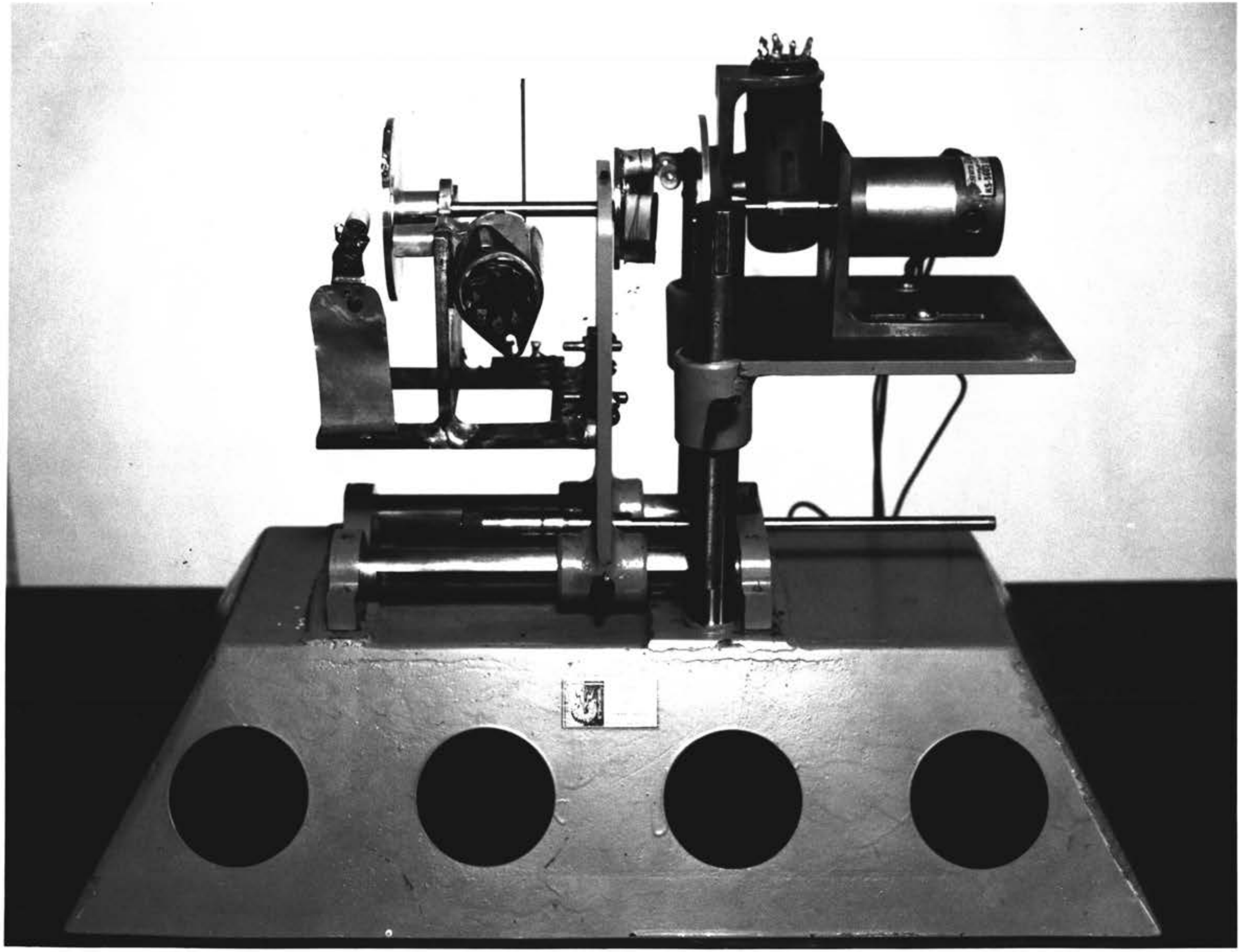

Figure 12. Photograph of the Electronic Dynamometer

usable angle of turn can easily be extended to sixty or seventy degrees.

A valuable addition to the instrument is planned. A circuit for multiplying the torque and speed together will be designed and this circuit will then be metered and a direct reading of horsepower will be added to the instrument.

Nothing has been said of the power required for the operation of the dynamometer. In the final unit a regulated power supply to furnish the 250 volts required will be built into the instrument. There will also be a voltage source for supplying the energy to the lamps used, so that the only external source required for the instrument itself will be 115 volts, 60 cycles. It was decided not to build a power supply in the instrument for supplying the power to the motor under test because of the many different voltages which would be needed. The base of the dynamometer will be large enough to house all circuits needed. The instruments for measuring speed, torque, and horsepower will be mounted on the base as shown in Figure 12, so that no additional equipment will be necessary.

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Miller, P. H., Jr. "Variable Speed Motor and Electric Tachometer." Review of Scientific Instruments, (December, 1944), 348.

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